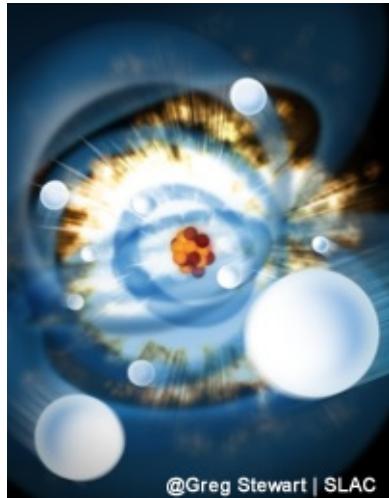


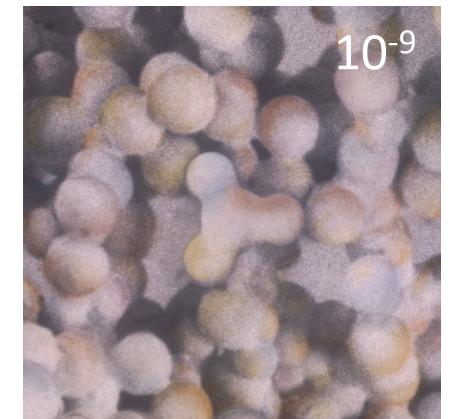
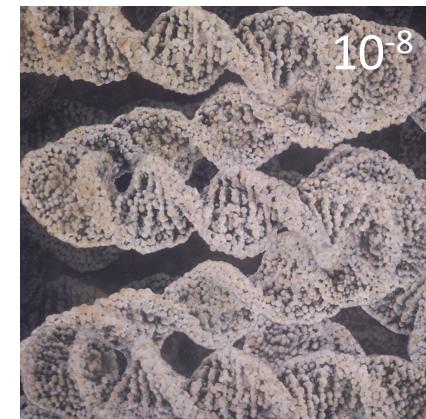
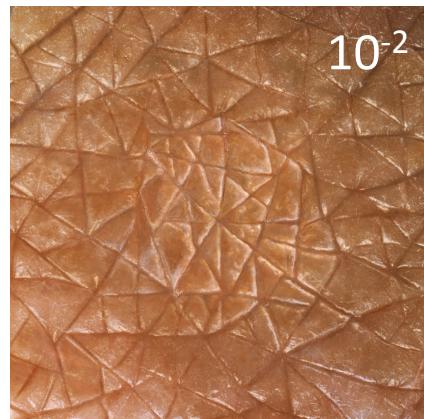
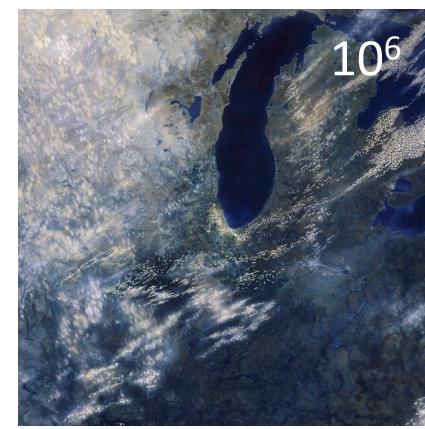
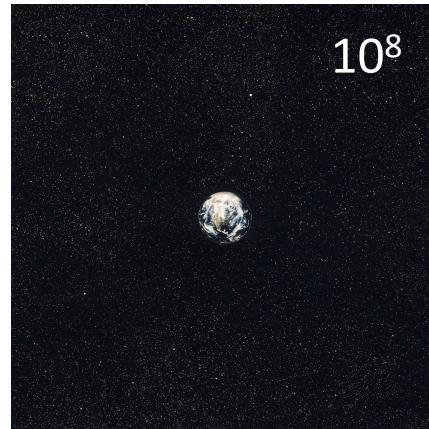
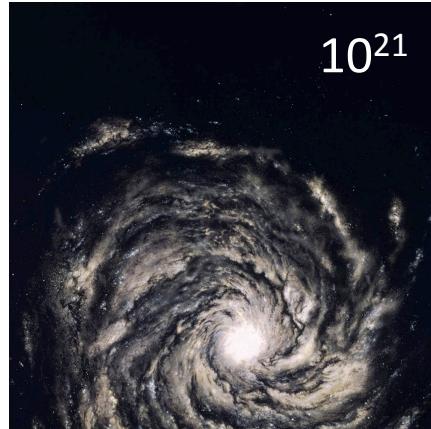
Frontiers in X-ray Science: the merger of x-rays and lasers

Linda Young
Argonne National Laboratory



Fermilab Colloquium
Fermilab, Batavia, IL
23 February 2011

Powers of ten - Eames & Morrison



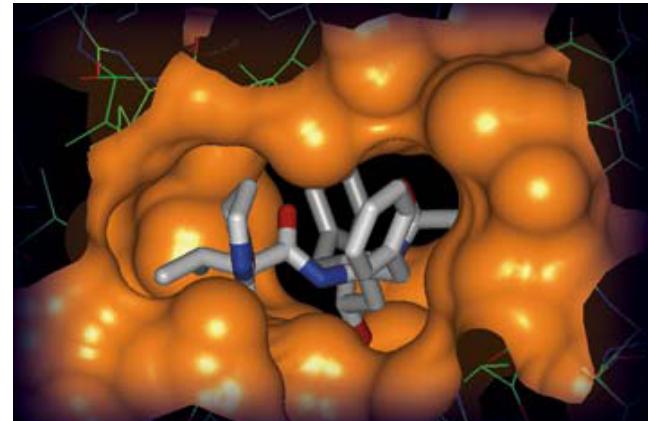
x-rays address complex systems at spatial scales over many orders of magnitude
with elemental, chemical, orientational and spin sensitivity



Synchrotron research on proteins has led to major advances in drugs to battle infection, HIV, cancer



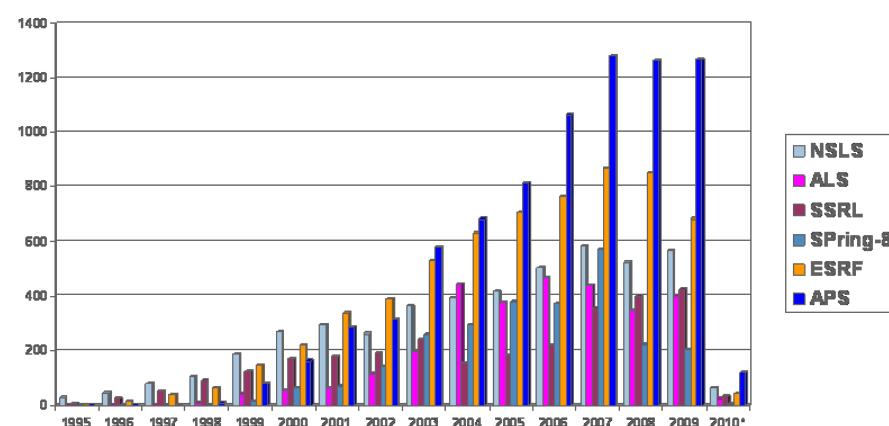
Renal cancer drug pazopanib™ developed in part based on APS research (GlaxoSmithKline)



Close-up view of the drug binding site within HIV protease ([Kaletra](#)®, Abbott).



Ramakrishnan, Steitz and Yonath
2009 Chemistry Nobel Laureates

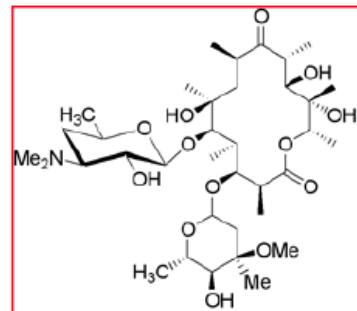


APS protein structure output is almost twice that of any other light source

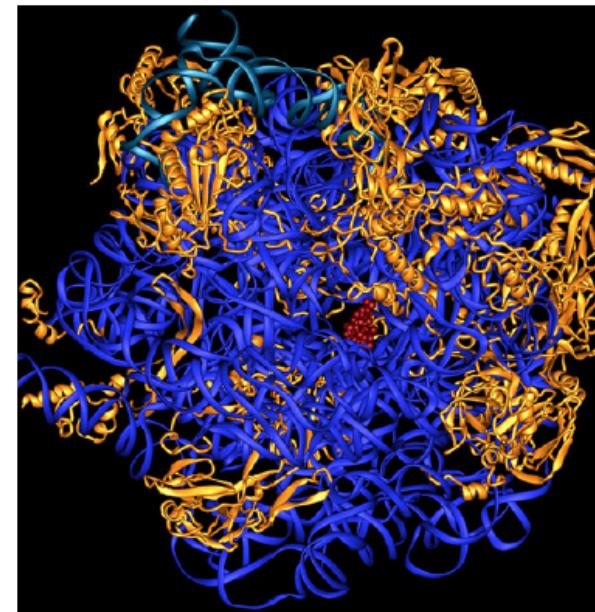


Designing antibiotics -

difference between bacterial and eukaryotic ribosomes is one amine group in the 2.5MD ribosome



Erythromycin – a macrolide antibiotic that blocks protein synthesis by binding to bacterial ribosomes but not to eukaryotic ribosomes



www.molgen.mpg.de



Outline

- Birth of a new machine, LCLS, World's First Hard X-ray FEL
- First experiments at LCLS – AMO
 - Non-resonant high intensity x-ray phenomena
LCLS Experiment 1: Oct 1 - 6, 2009
 - Resonant high intensity x-ray phenomena
LCLS Experiment 5: Oct 29 – Nov 3, 2009
- Towards single molecule imaging with x-rays
- Outlook

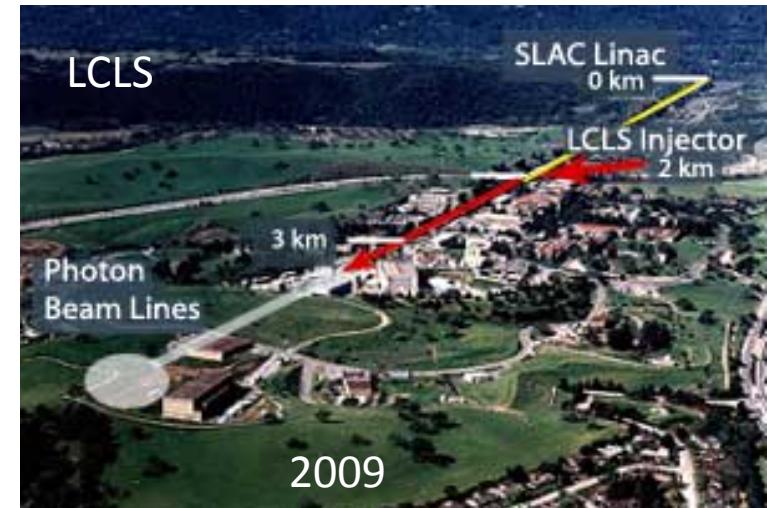


XFELs are here (LCLS) and more are coming soon!

Physics Today, May 2005

	LCLS (US)	DESY XFEL (Europe)	SCSS (Japan)
Pulse duration	<230 fs	100 fs	80 fs
Wavelength	1–64 Å	1–15 Å	1–50 Å
Repetition rate	120 Hz	10 Hz	60 Hz
Electron bunches per pulse	1	≤3000	1
Electron beam energy	4–14 GeV	≤20 GeV	≤8 GeV
Photons per pulse (×10 ¹²)	1.2 (at 1.5 Å)	1.2 (at 1 Å)	0.76 (at 1 Å)
Linac length	1 km	2 km	350 m
Estimated cost*	\$379 million	\$1 billion	\$330 million
Estimated start date	2009	2012	2010

*Estimates include varying amounts of instrumentation and different methods of accounting.



Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing 3-km linac

Proposed by C. Pellegrini in 1992

1.5-15 Å
(14-4.3 GeV)

Injector (35°)
at 2-km point

Existing 1/3 Linac (1 km)

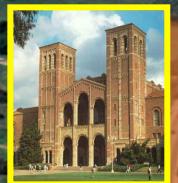
New e⁻ Transfer Line (340 m)

X-ray Transport
Line (200 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment
Hall



UCLA



Argonne
NATIONAL LABORATORY

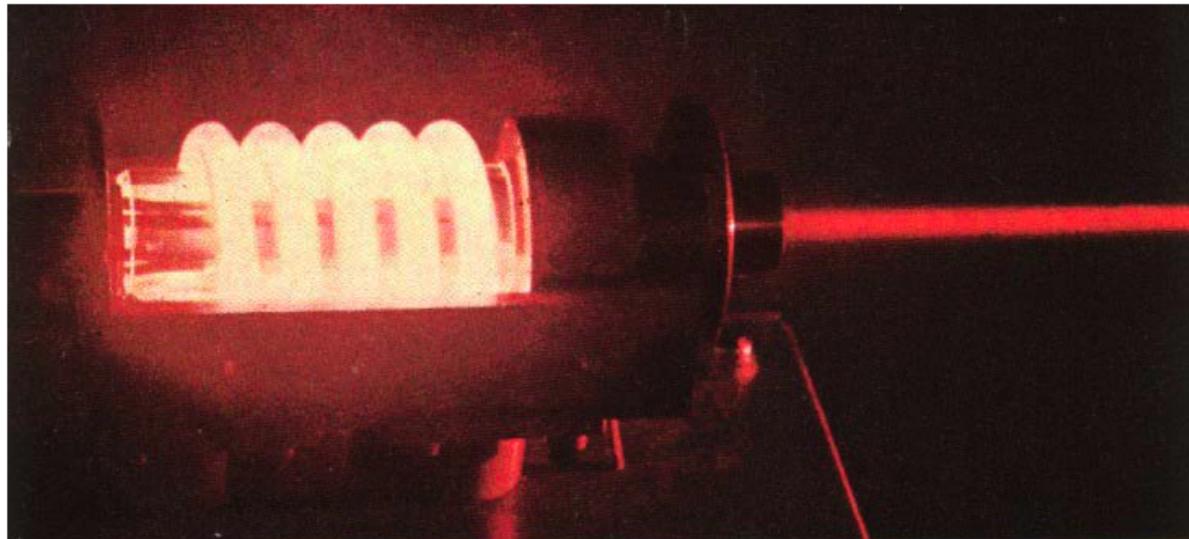


LLNL

Laser Fest: 50th anniversary of the laser



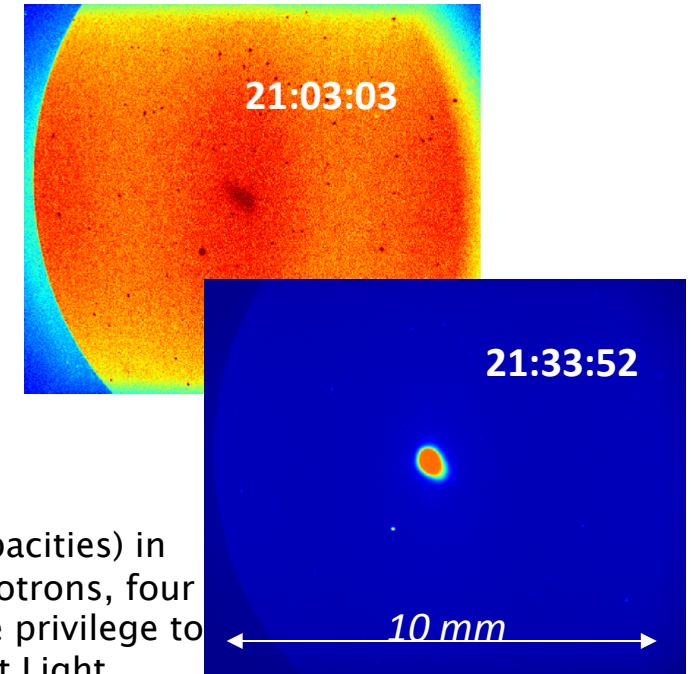
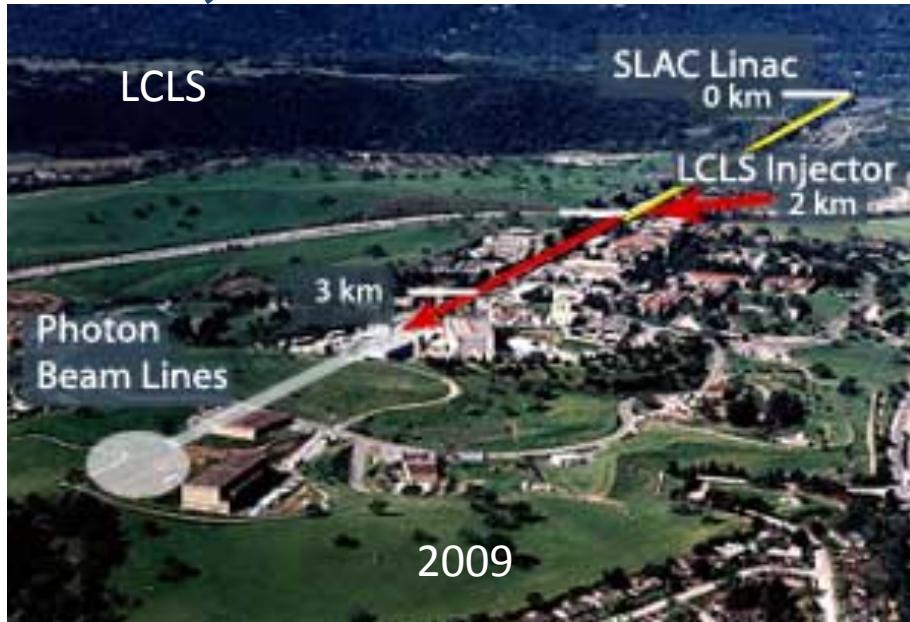
May 17, 1960: Ted Maiman's ruby laser



T. Maiman, "Stimulated Optical Radiation in Ruby," Nature (London) 187, 493 (1960).



April 10, 2009: LCLS lasers at 1.5 Angstroms



In my life before SLAC, I had the privilege to participate (in various capacities) in the design, construction and commissioning of two linacs, two synchrotrons, four storage rings and three FELs (free-electron lasers). Now I have had the privilege to be in SLAC's Main Control Center on April 10, when the Linac Coherent Light Source became a 1.5 Ångstrom laser. I don't expect I will ever, as long as I live, see such a beautiful, smooth turn-on of any light source. With each undulator placed on the beam path, the FEL power increased by a factor of about 2.3; two hours into the first attempt at lasing, the pinpoint of FEL light from twelve undulators was nearly 2,000-fold more intense than plain old undulator radiation. The team called it quits at 11:30 p.m. that night. When they returned at 8:00 a.m. the next morning, the FEL light came back as soon as the shutter was opened.

- John Galayda

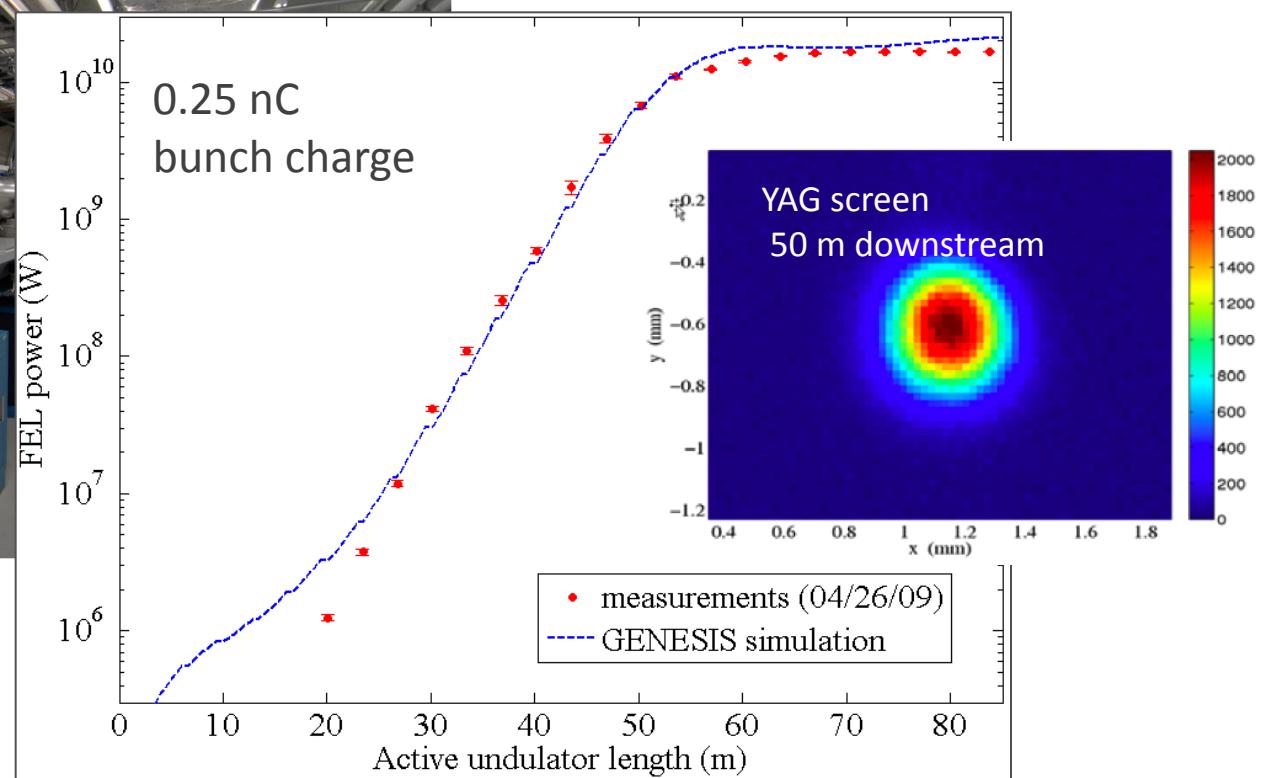
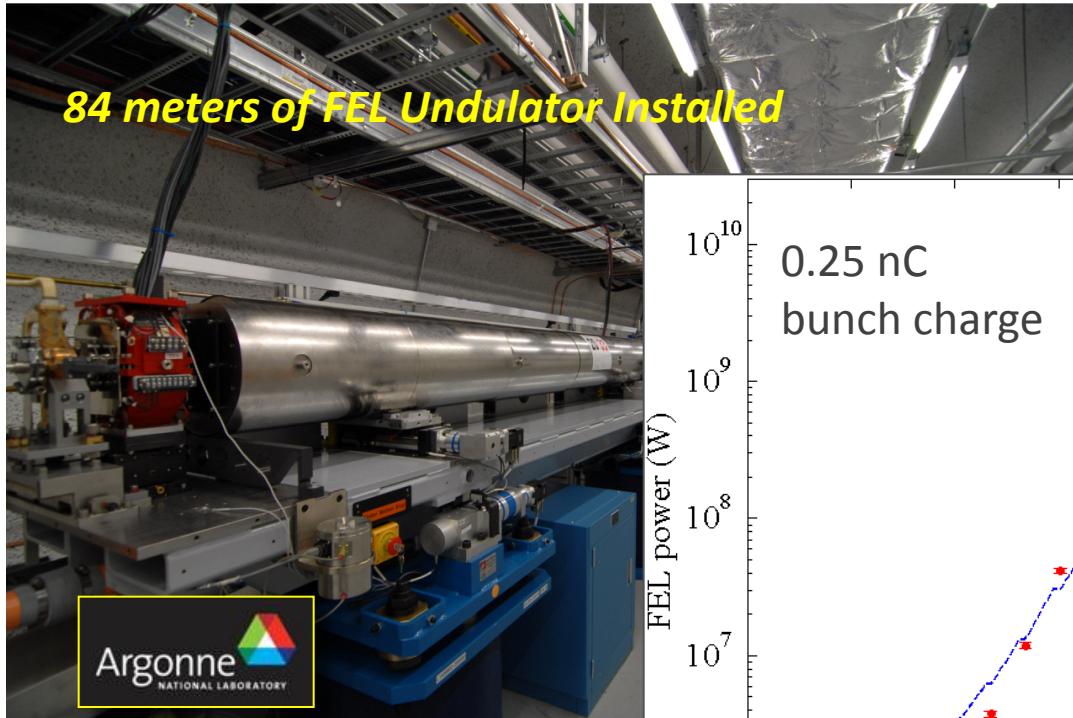


From John Galayda

Yes I Do Smile on Occasion



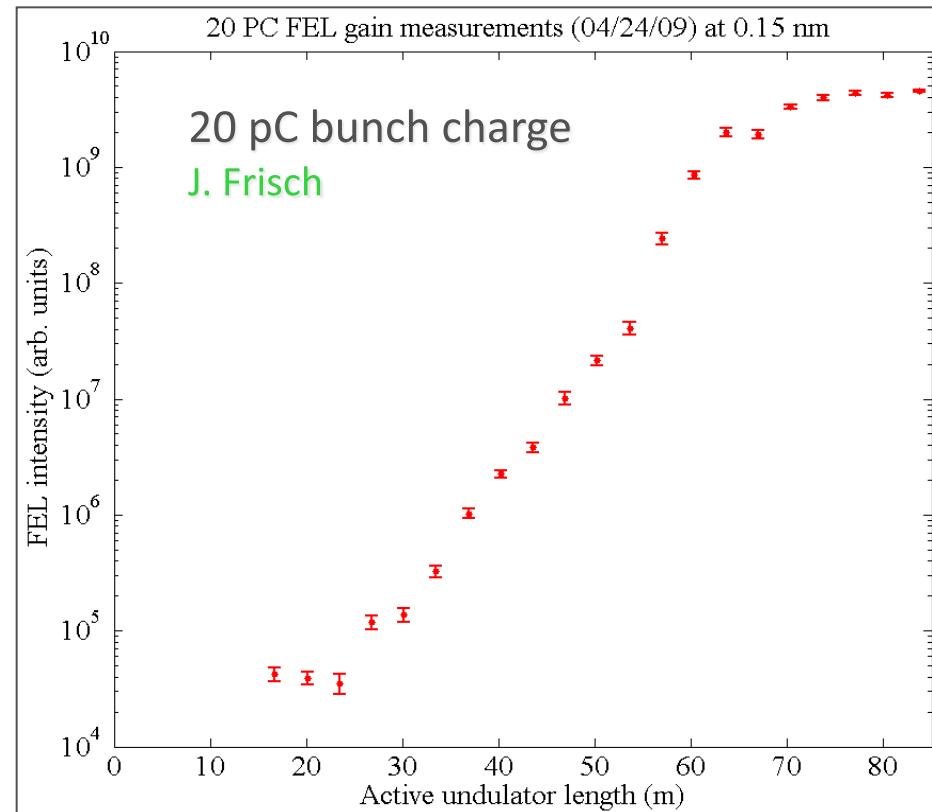
LCLS saturation at 1.5 Å



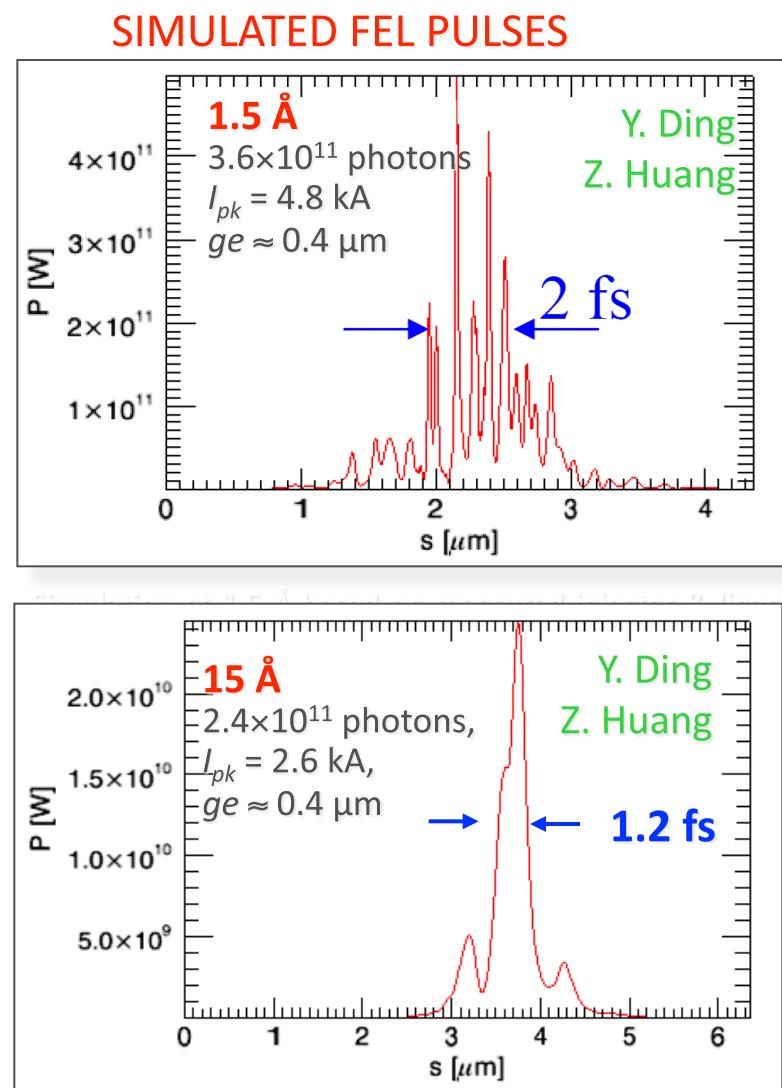
- Saturation after ~65 meters of undulator!



Short pulse capability ~2 fs with low bunch charge ?



Simulation at 15 Å based on measured injector & linac beam & *Elegant* tracking, with CSR & 20 pC.



From P. Emma: See Y. Ding et al PRL 102, 254801 (2009)



First lasing and operation of an ångstrom-wavelength free-electron laser

P. Emma et al.

Table 1 | Design and typical measured parameters for both hard (8.3 keV) and soft (0.8–2.0 keV) X-rays. The ‘design’ and ‘hard’ values are shown only at 8.3 keV. Stability levels are measured over a few minutes.

Parameter	Design	Hard	Soft	Unit
Electrons				
Charge per bunch	1	0.25	0.25	nC
Single bunch repetition rate	120	30	30	Hz
Final linac e^- energy	13.6	13.6	3.5–6.7	GeV
Slice [†] emittance (injected)	1.2	0.4	0.4	μm
Final projected [†] emittance	1.5	0.5–1.2	0.5–1.6	μm
Final peak current	3.4	2.5–3.5	0.5–3.5	kA
Timing stability (r.m.s.)	120	50	50	fs
Peak current stability (r.m.s.)	12	8–12	5–10	%
X-rays				
FEL gain length	4.4	3.5	~1.5	m
Radiation wavelength	1.5	1.5	6–22	\AA
Photons per pulse	2.0	1.0–2.3	10–20	10^{12}
Energy in X-ray pulse	1.5	1.5–3.0	1–2.5	mJ
Peak X-ray power	10	15–40	3–35	GW
Pulse length (FWHM)	200	70–100	70–500	fs
Bandwidth (FWHM)	0.1	0.2–0.5	0.2–1.0	%
Peak brightness (estimated)	8	20	0.3	$10^{32} *$
Wavelength stability (r.m.s.)	0.2	0.1	0.2	%
Power stability (r.m.s.)	20	5–12	3–10	%

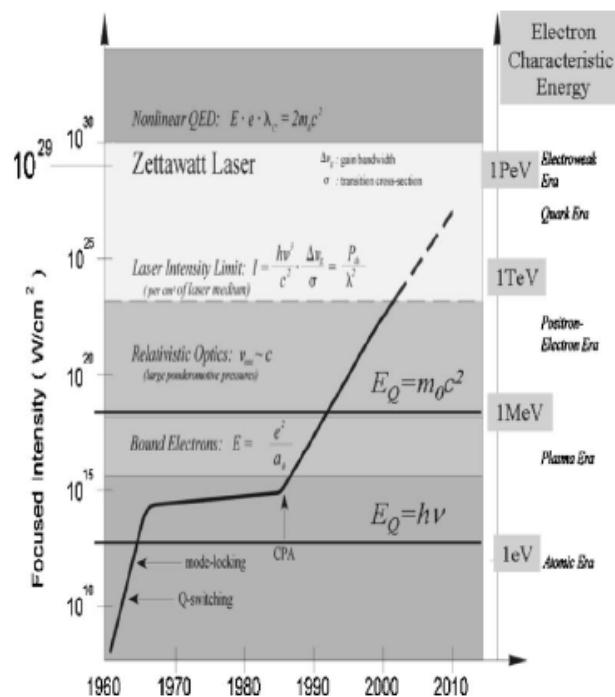
*Brightness is photons per phase space volume, or photons $\text{s}^{-1} \text{mm}^{-2} \text{mrad}^{-2}$ per 0.1% spectral bandwidth.

[†]‘Slice’ refers to femtosecond-scale time slices and ‘projected’ to the full time-projected (that is, integrated) emittance of the bunch.

Compare the evolution of high intensity optical and x-ray sources

High-intensity at optical wavelengths

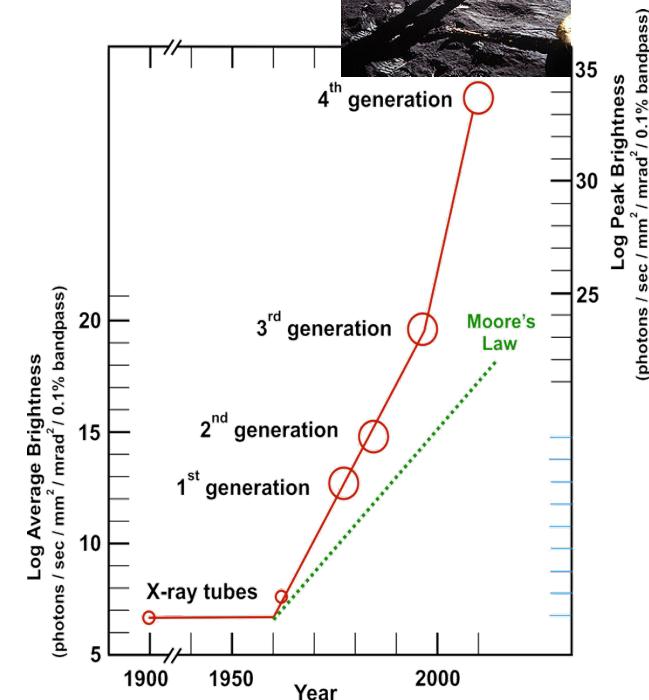
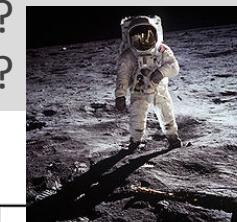
- high harmonic generation
- tabletop coherent x-ray radiation
- attosecond pulses



G. Mourou RMP 2006

High-intensity at x-ray wavelengths

?



D. Moncton, George Brown



Contrast optical and x-ray interactions at high intensity

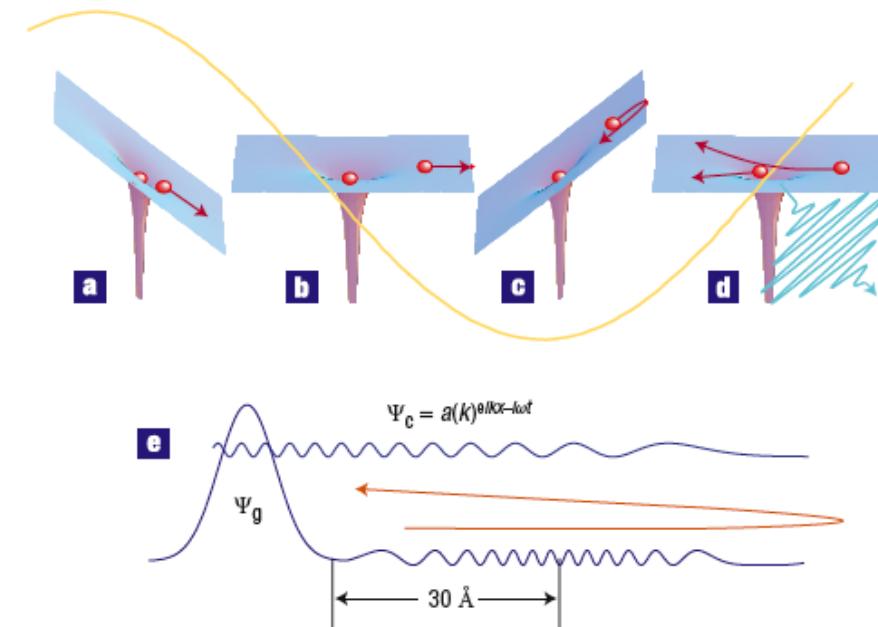
At long wavelengths - laser-driven electron dynamics is dominant
... not so at short wavelengths

electron ponderomotive energy (au)

$$U_p = I/4\omega^2$$

displacement

$$\alpha = E/\omega^2$$



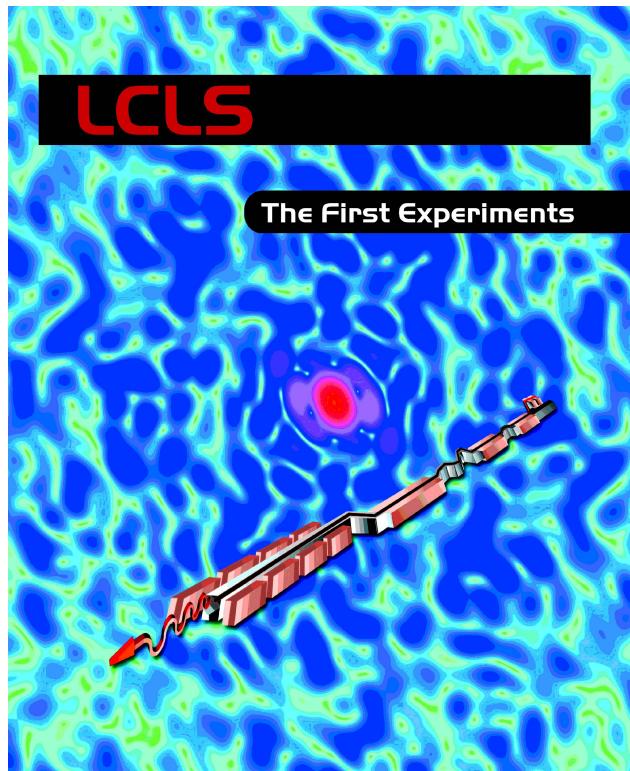
Graphic from Corkum & Krausz
Nature Physics (2007)

Ti:sapphire laser (1.55 eV) PW/cm²
 $U_p \sim 60 \text{ eV} \text{ & } \alpha \sim 50 \text{ au}$

LCLS (800 eV) 100 PW/cm²
 $U_p \sim 25 \text{ meV} \text{ & } \alpha \sim 0.003 \text{ au}$



Science Drivers for LCLS



AMO: Atomic Molecular and Optical

SXR: Soft X-ray Materials Science

XPP: X-ray Pump-Probe

XCS: X-ray Correlation Spectroscopy

CXI: Coherent X-ray Imaging

MEC: Materials in Extreme Conditions

AMO

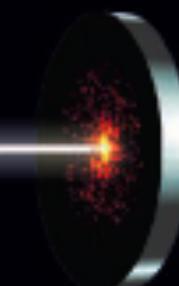
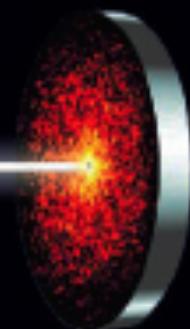
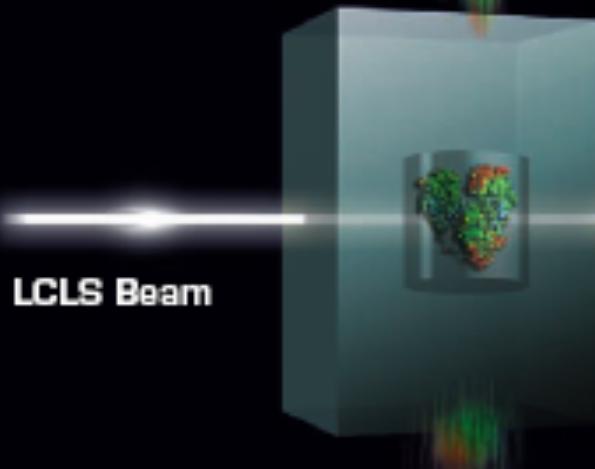
- Understand and control x-ray atom/molecule interactions at ultrahigh x-ray intensity as a foundation for other applications.
- Provide diagnostics of the LCLS radiation



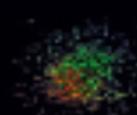
Protein Molecule
Injection



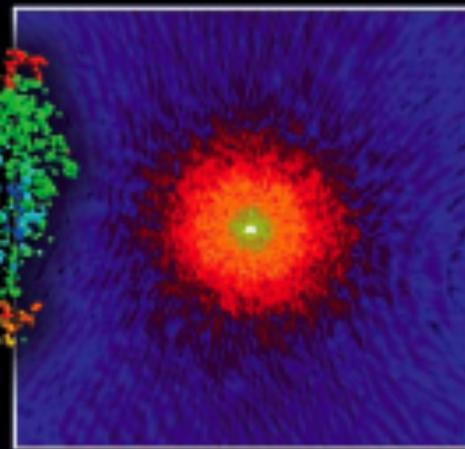
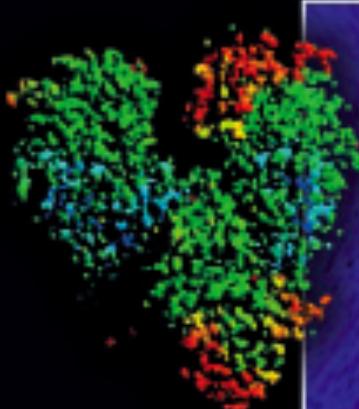
Single molecule imaging



To Mass
Spectrometer



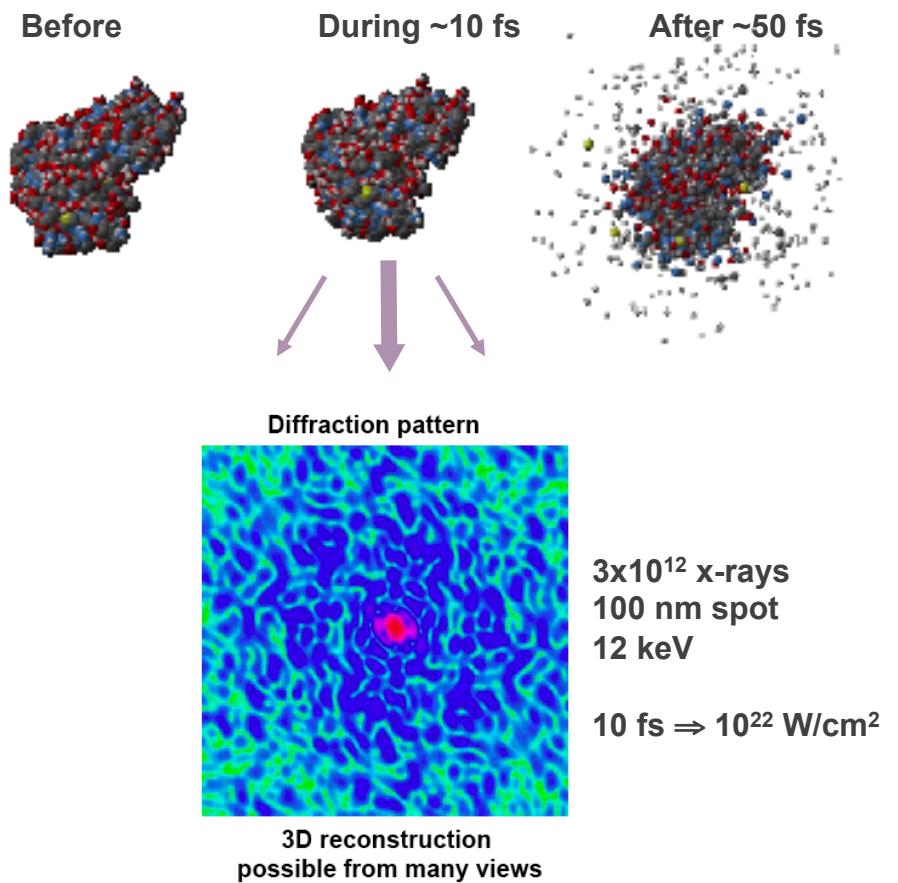
Protein
Molecule



Operating with ultrafast pulses, LCLS will take images of molecules dropped into the x-ray beam. Scientists will merge the series of diffraction patterns of the molecules in many different positions. The resulting three-dimensional reconstruction will reveal the structures of proteins that cannot be crystallized and thus studied any other way.

AMO questions at the ultraintense x-ray frontier

- fundamental nature of x-ray damage at high intensity
 - Coulomb explosion
 - electronic damage
 - behavior at 10^{22} W/cm^2 - 1\AA
- nonlinear x-ray processes
 - role of coherence
- quantum control of inner-shell processes



Neutze, Wouts, van der Spoel, Weckert, Hajdu Nature 406, 752 (2000)



LCLS Experiment 1 - Oct 1, 2009

Nature of the electronic response to

10^5 x-rays/ \AA^2

80 - 340 fs

800 - 2000 eV

$\sim 10^{18}$ W/cm²

Original single molecule imaging parameters, Neutze et al. Nature (2000)

3×10^{12} x-rays/(100 nm)² = 3×10^6 x-rays/ \AA^2

10 fs

$\sim 10^{22}$ W/cm²



ARTICLES

Femtosecond electronic response of atoms to ultra-intense X-rays

L. Young¹, E. P. Kanter¹, B. Krässig¹, Y. Li¹, A. M. March¹, S. T. Pratt¹, R. Santra^{1,2}, S. H. Southworth¹, N. Rohringer³, L. F. DiMauro⁴, G. Doumy⁴, C. A. Roedig⁴, N. Berrah⁵, L. Fang⁵, M. Hoener^{5,6}, P. H. Bucksbaum⁷, J. P. Cryan⁷, S. Ghimire⁷, J. M. Glownia⁷, D. A. Reis⁷, J. D. Bozek⁸, C. Bostedt⁸ & M. Messerschmidt⁸



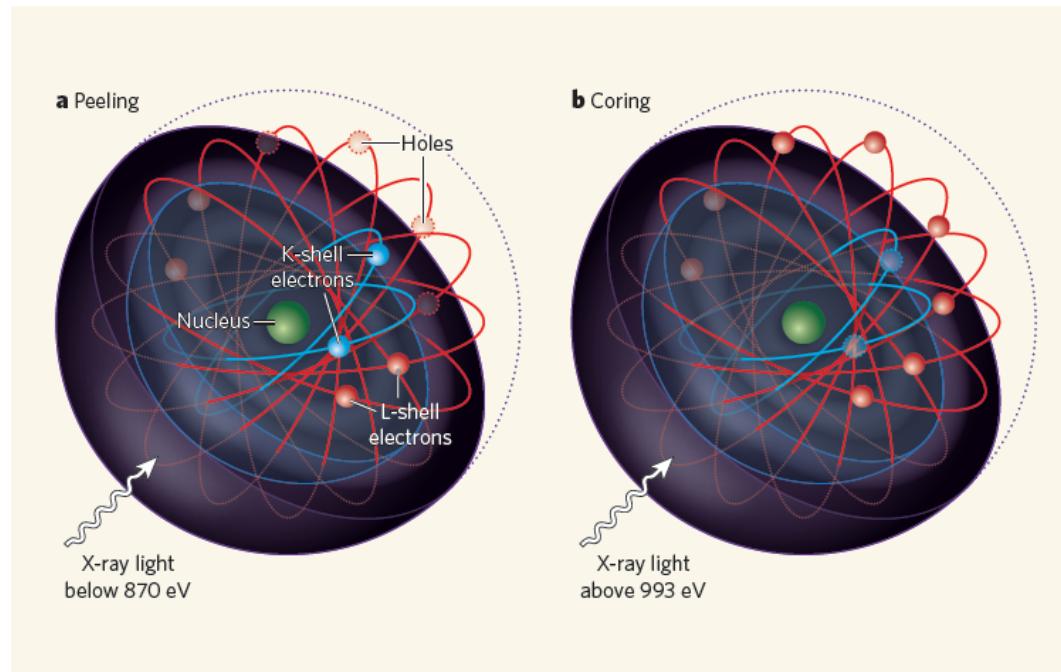
NEWS & VIEWS

ATOMIC PHYSICS

X-ray laser peels and cores atoms

Justin Wark

The world's first kiloelectronvolt X-ray laser produces such a high flux of photons that atoms can be 'cored'. In other words, the light source can knock out both the electrons of an atom's innermost shell.



Our approach to understanding ultraintense x-ray interactions

- Start with a well-characterized target

Binding energies in neutral neon

2p : ~21 eV

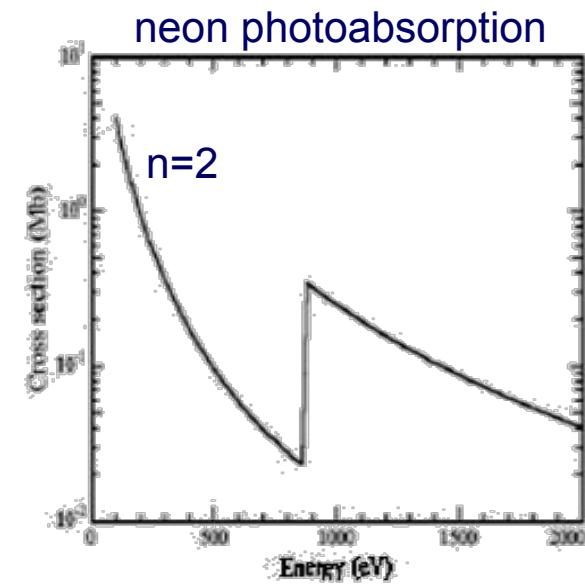
2s : ~48 eV

1s : ~870 eV

Inner-shell excitation

Auger yield 98%

Auger clock - τ_{1s} : 2.4 fs

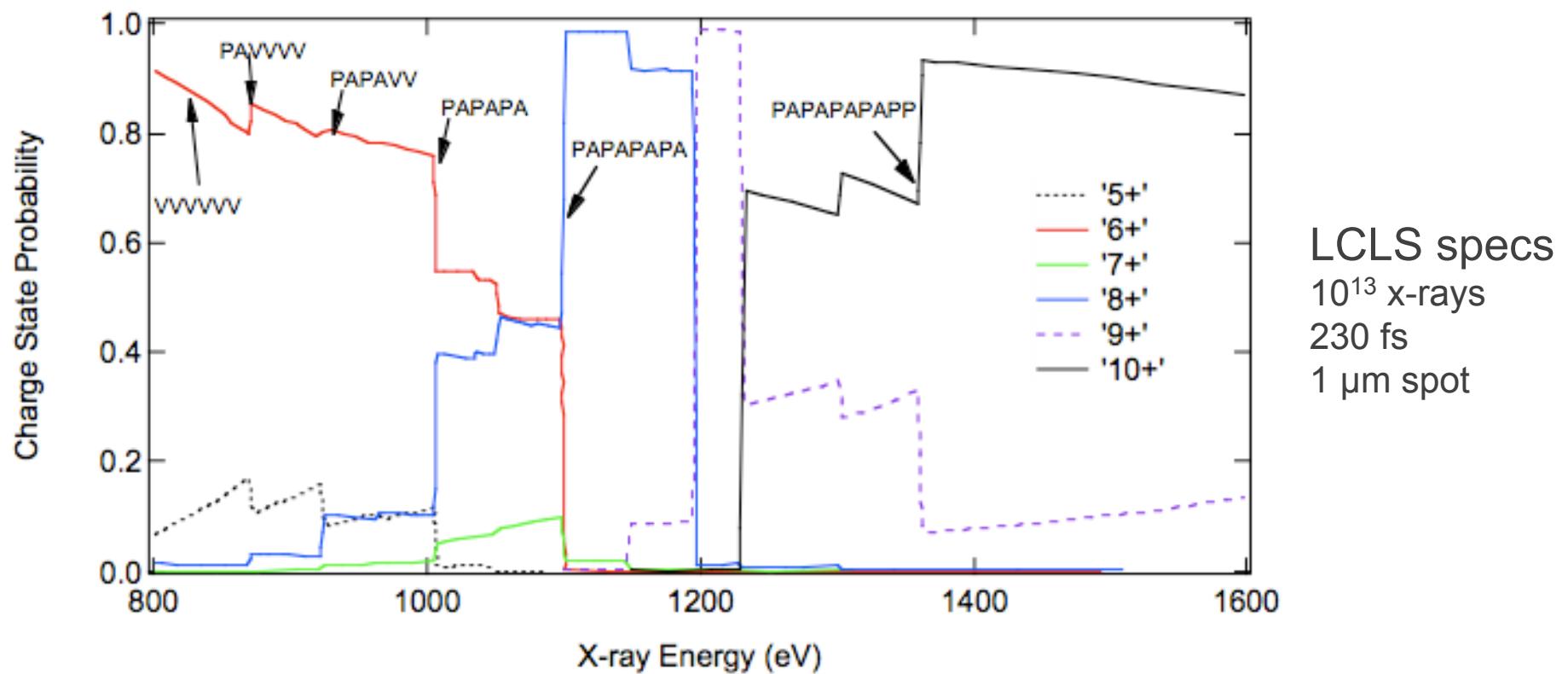


- Probe changes in interaction from outer- to inner-shell between 800-2000 eV



Guided by theory

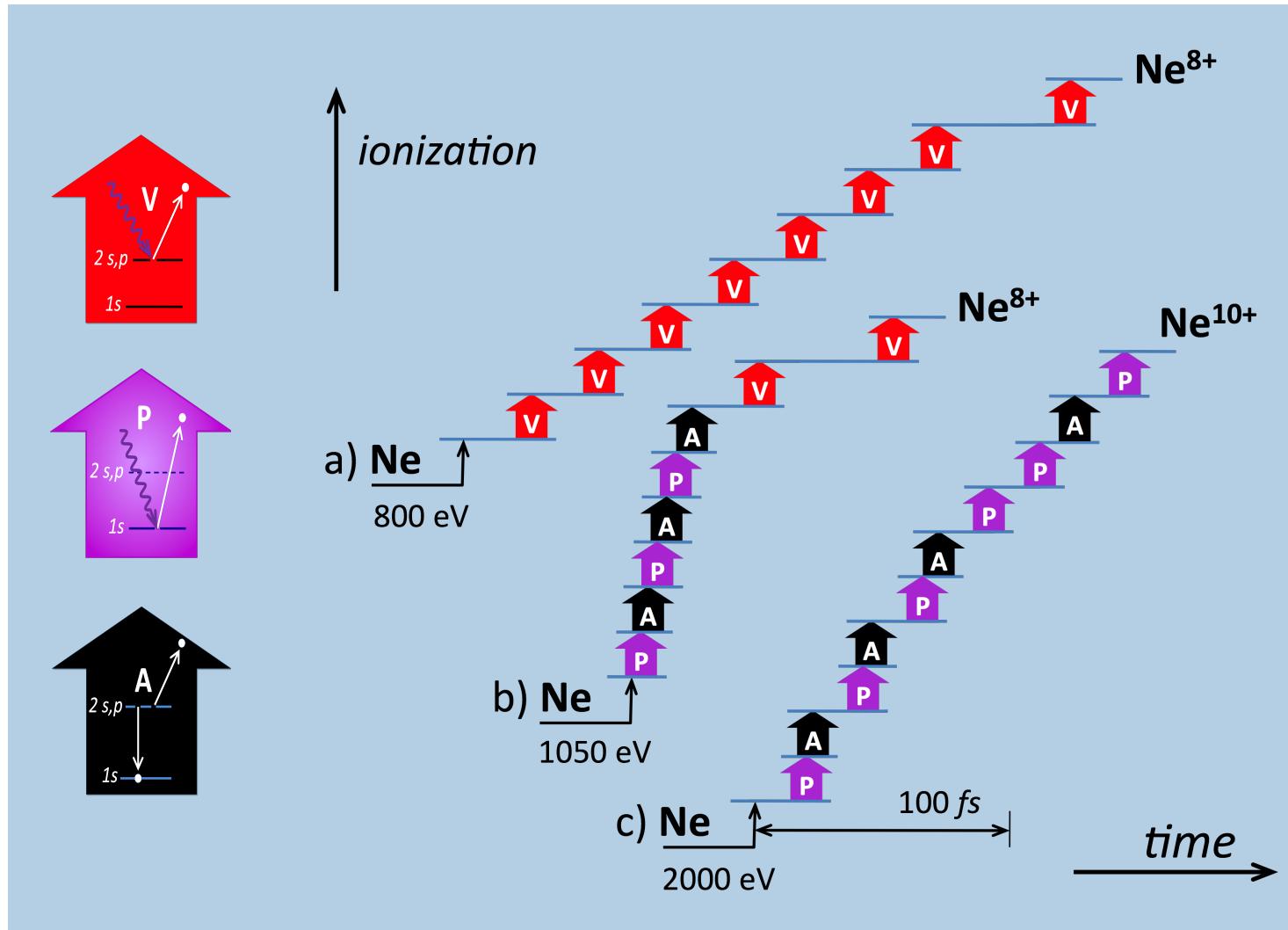
Theory: Rohringer & Santra, PRA 76, 033416 (2007)



Three target energies: 800 eV, 1050 eV, 2000 eV



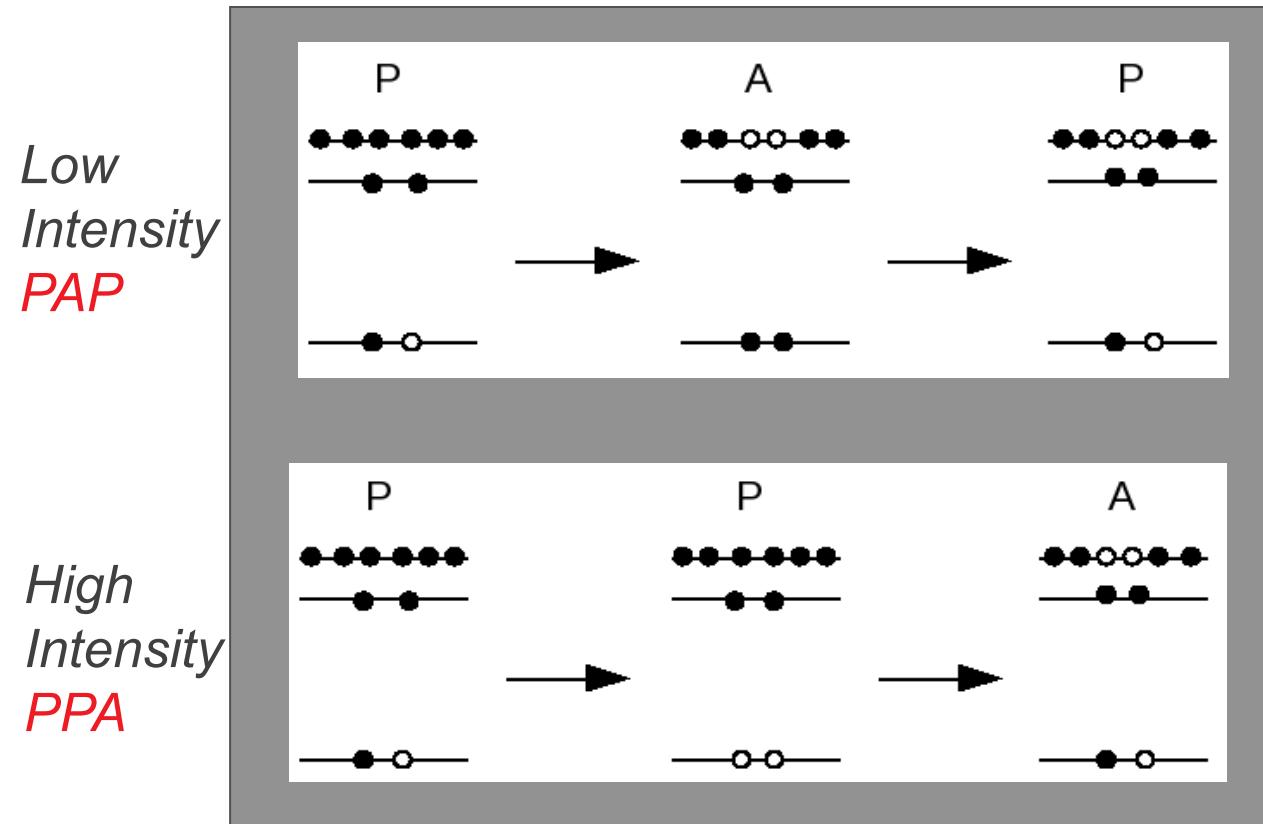
Valence ionization, core ionization and Auger decay



Sequential single photon processes dominate the interaction



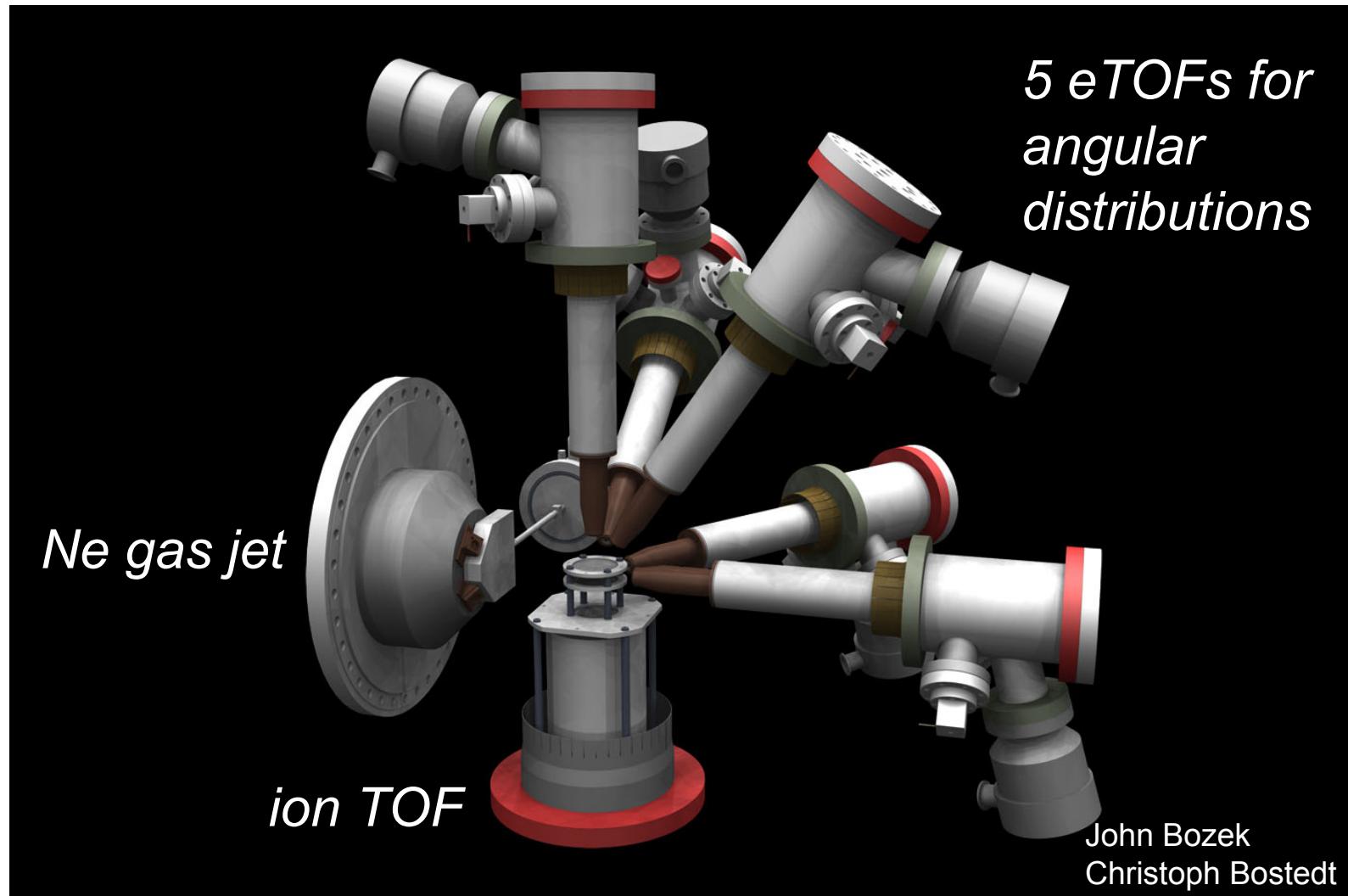
How does one arrive at a particular charge state?



- Hollow atoms produced at high x-ray intensity
- Electron spectroscopy can define the mechanism

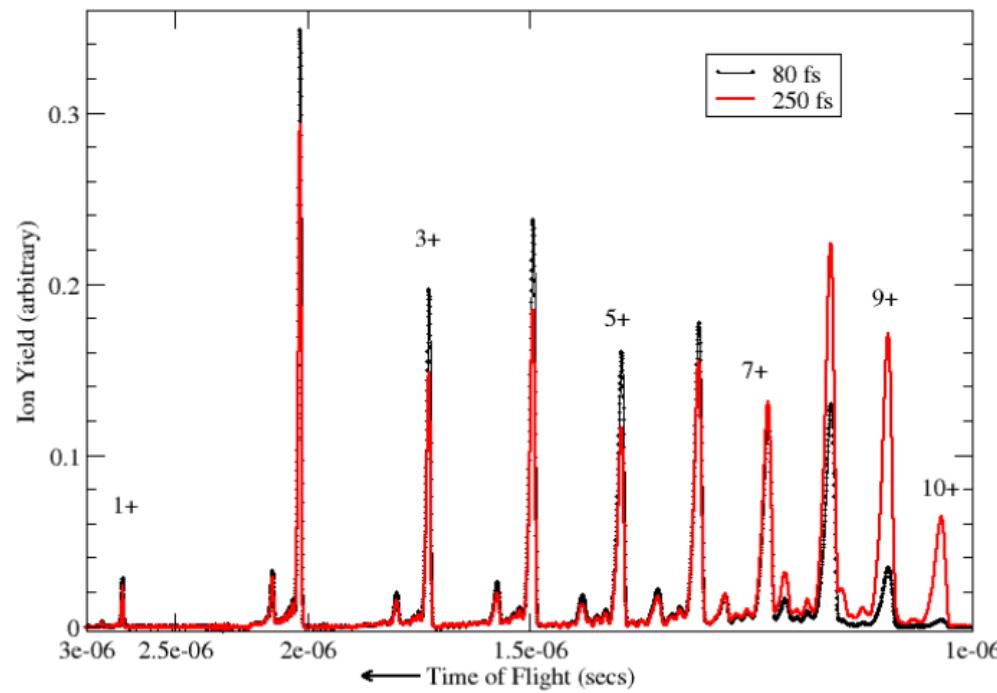


High field physics chamber



Day 1 - two interesting observations

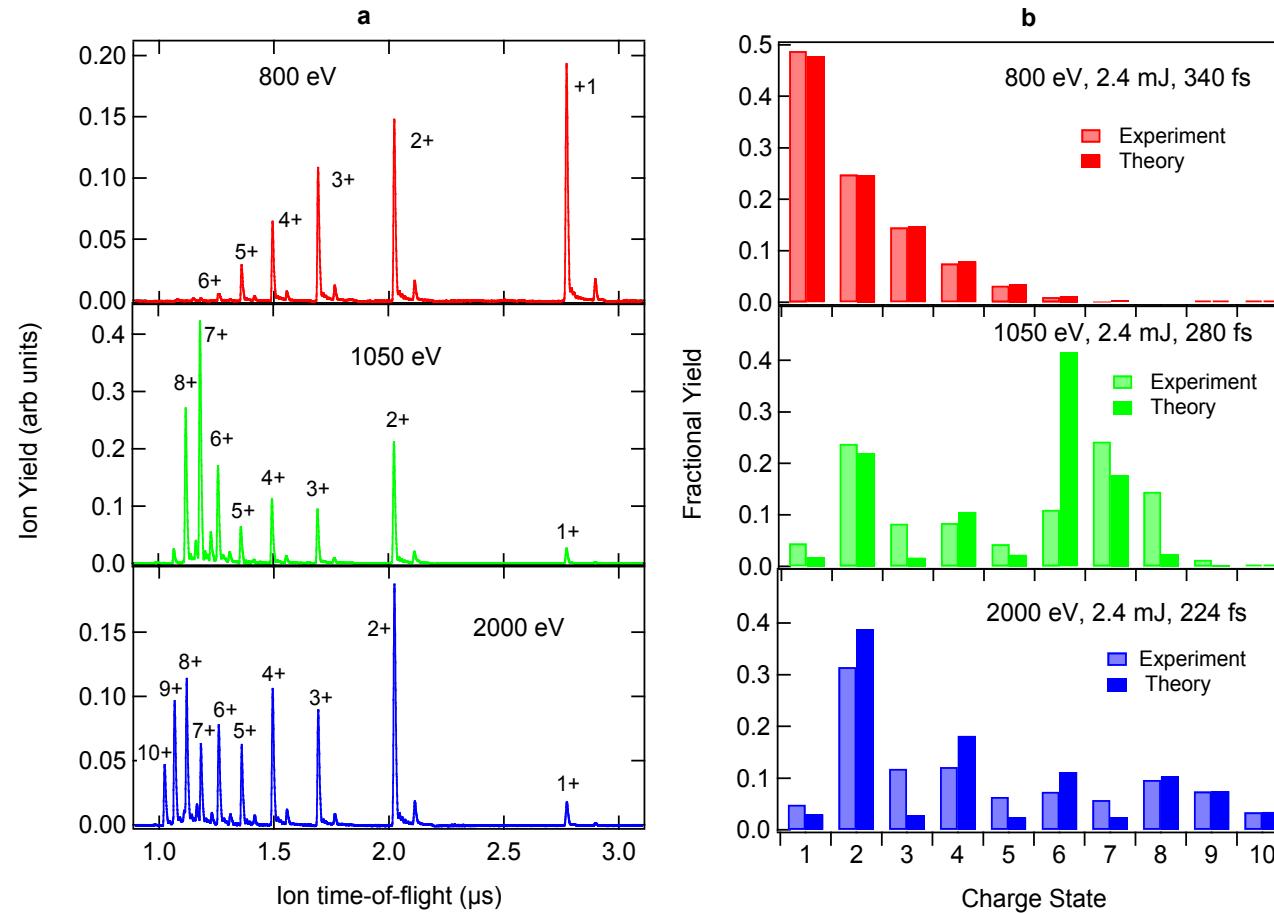
- Single ~100 fs pulse at 2000 eV fully strips neon
6-photon, 10-electron process



- Shorter pulses with equal pulse energy & fluence suppress absorption & damage.



Theory can model ultraintense x-ray-induced electronic damage in neon



Theory

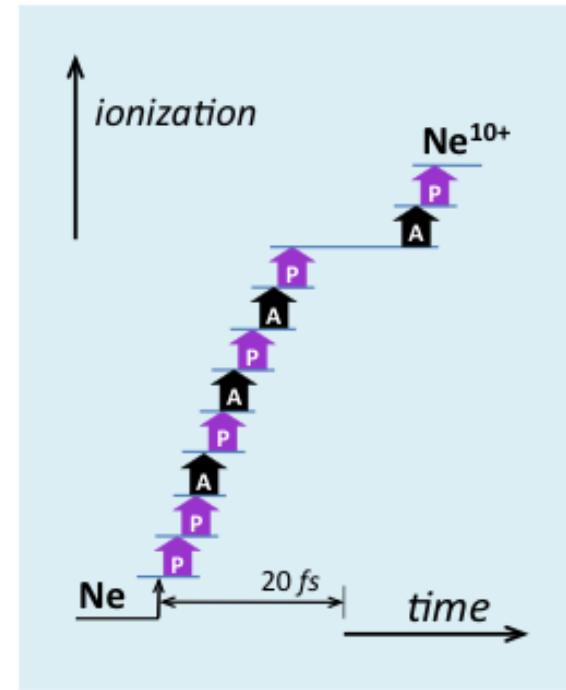
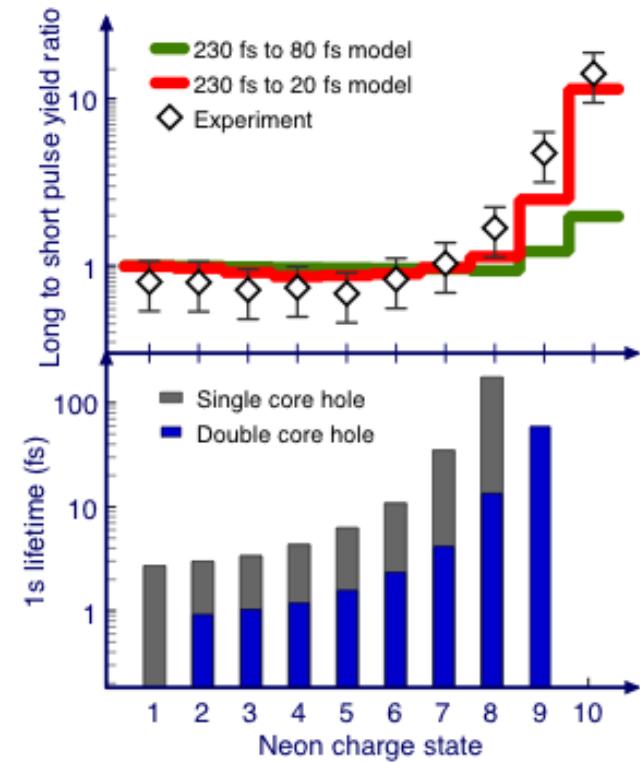
- Intensity averaged
- Fluence determined by experiment

Consistent with “measured” pulse energy and focus.



Sang-Kil Son, Robin Santra – refined calcs include shakeoff

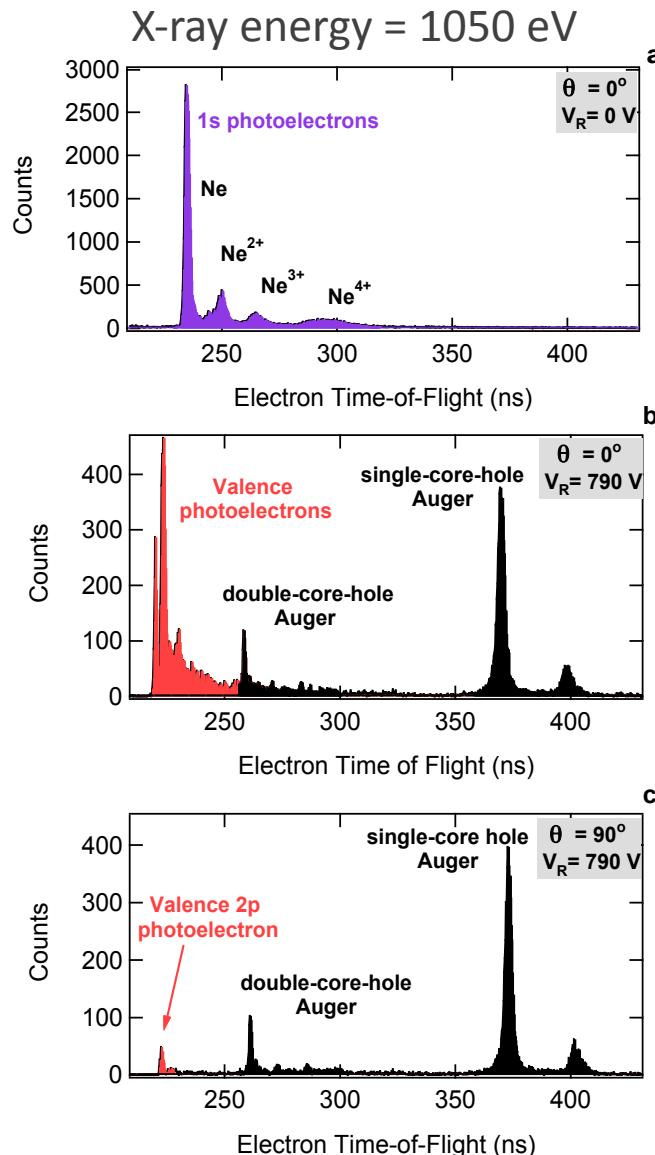
Atoms become transparent at high x-ray intensity !



- x-ray absorption is due to the presence of 1s electrons
- high x-ray intensities eject 1s electrons rendering the atom transiently transparent
- slowing atomic clocks create transparency at surprisingly long timescales



Electron spectrometers track ionization mechanism



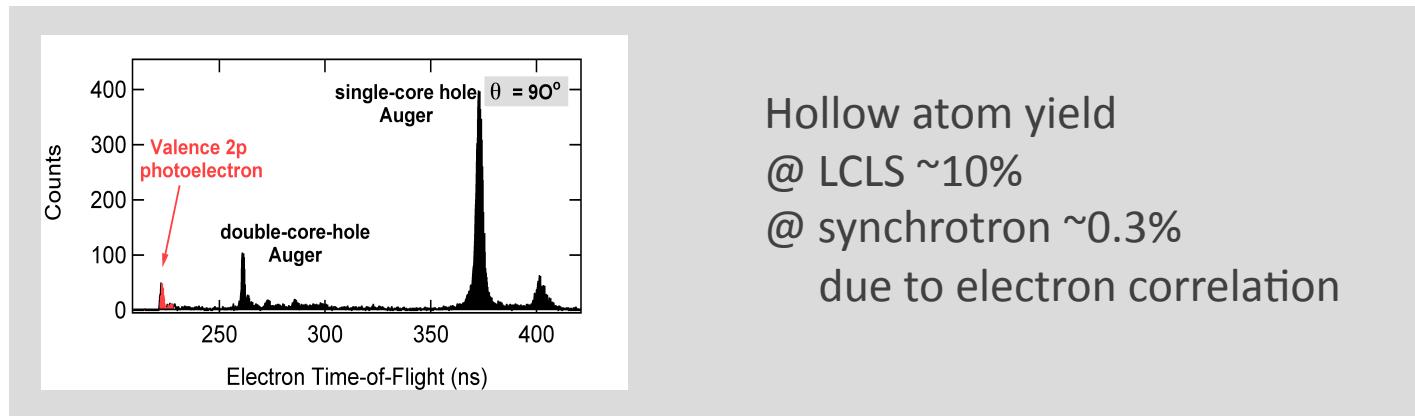
“Slow” 1s photoelectrons along x-ray polarization axis

“Fast” valence photoelectrons and Augers along polarization axis

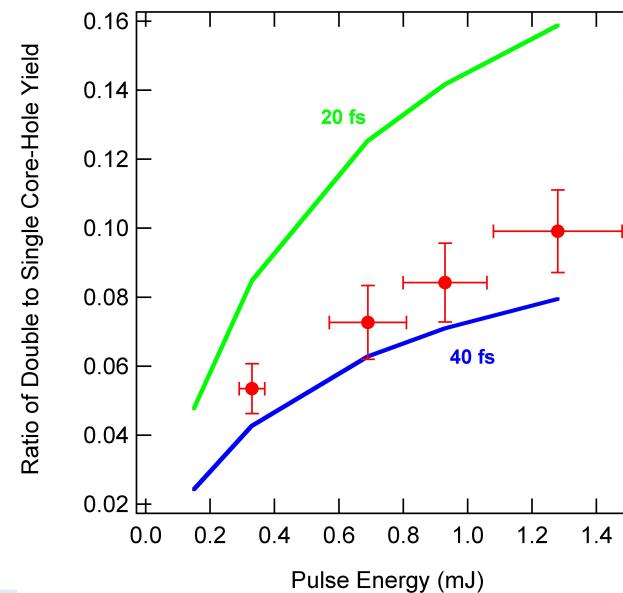
Clean hollow atom signature
double-core-hole Auger
 $\theta = 90^\circ$



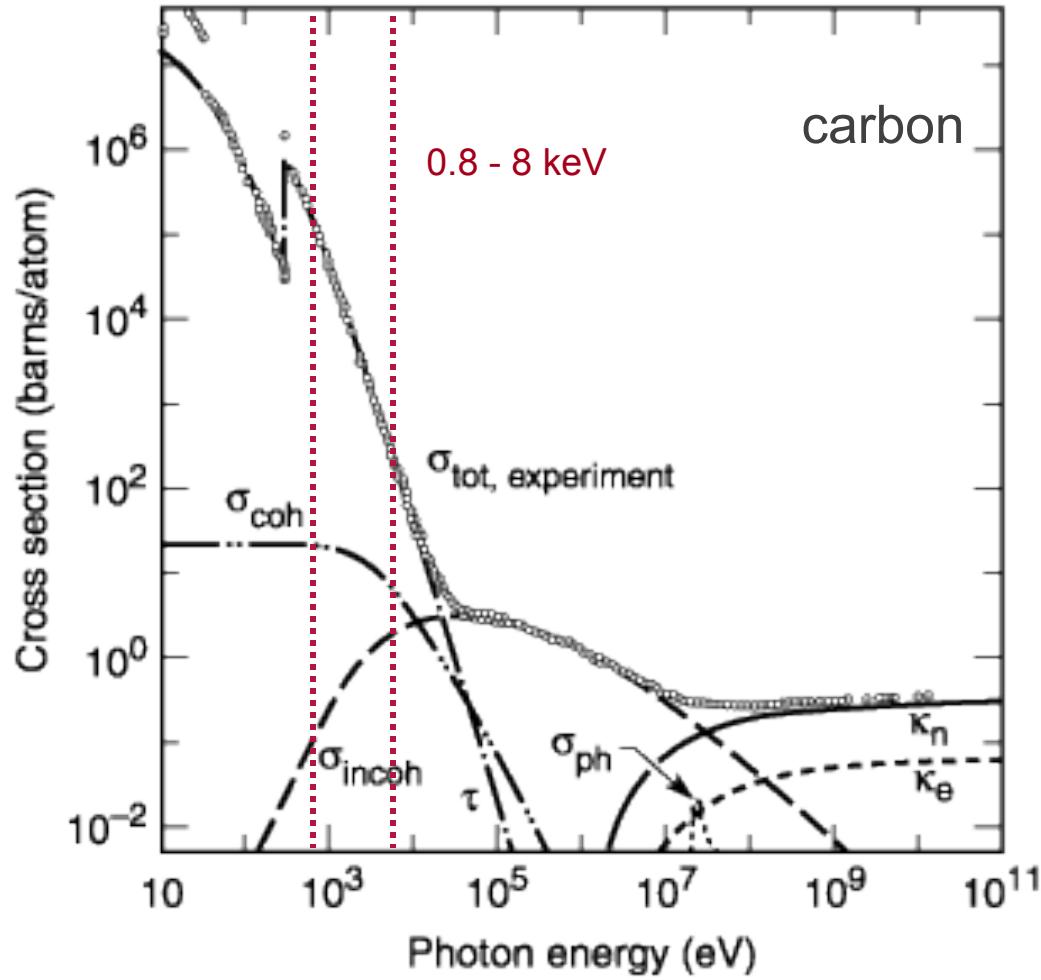
Hollow atom production: deliberate, huge and an indicator of x-ray pulse duration



1050 eV,
nominal electron bunch
duration ~80 fs



Absorption vs scattering: normal and hollow atoms



	$\frac{\sigma_{photo}}{\sigma_{elastic}}$	$\frac{\sigma_{Compton}}{\sigma_{elastic}}$
2 keV	360	0.05
8 keV	20	0.60
8 keV hollow	2	

Impact of hollow atom
formation on coherent x-
ray scattering
Sang-Kil Son, LY, RS
Phys. Rev A. in press



Summary of ultra-intense x-ray interaction phenomena

- Target changes during a single 100 fs x-ray pulse at fluences similar to that for single molecule imaging
 - six-photon, ten-electron stripping of neon ($\sim 10^{12}/\mu\text{m}^2$)
 - multiphoton absorption probability high when fluence $> 1/\sigma$
- Intensity-induced x-ray transparency – a general phenomena
 - transient x-ray transparency caused by formation of hollow atoms
 - hollow atoms $\sigma_{\text{scatt}}/\sigma_{\text{abs}}$ is increased – advantageous for imaging
- Straightforward rate equation calculations capture essential physics
- Femtosecond time-scale atomic processes provide FEL diagnostics



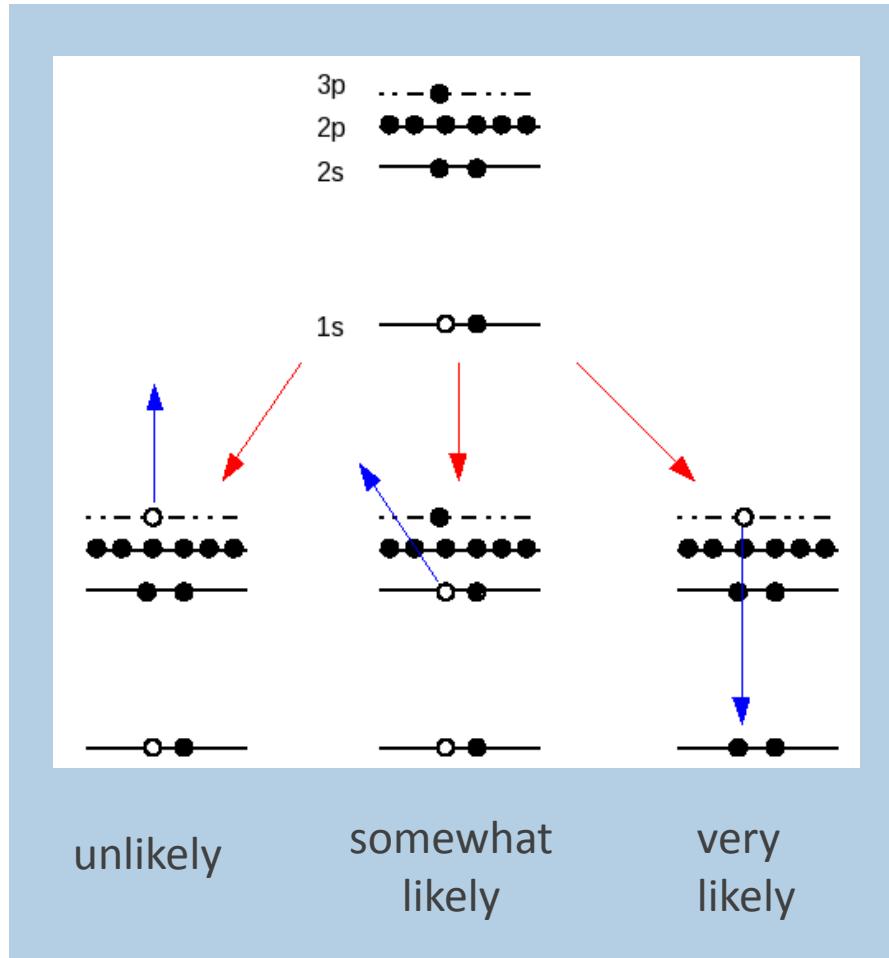
LCLS Experiment 5

Resonant x-ray processes at high intensity

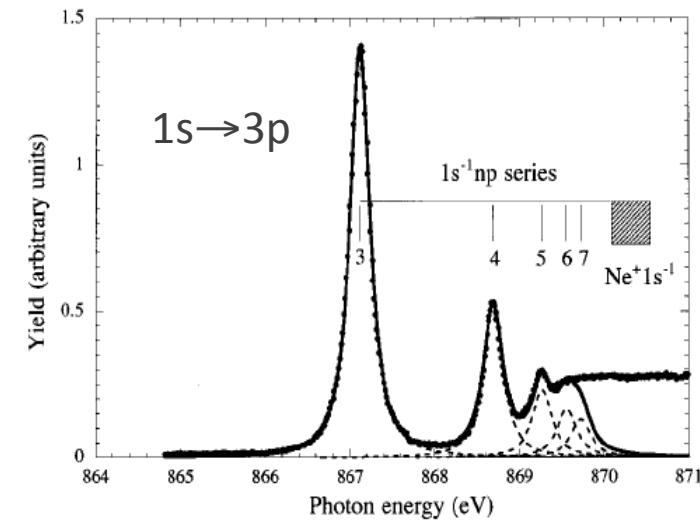


Can we control inner-shell electron dynamics?

“Rabi flopping” may inhibit Auger decay & x-ray damage.



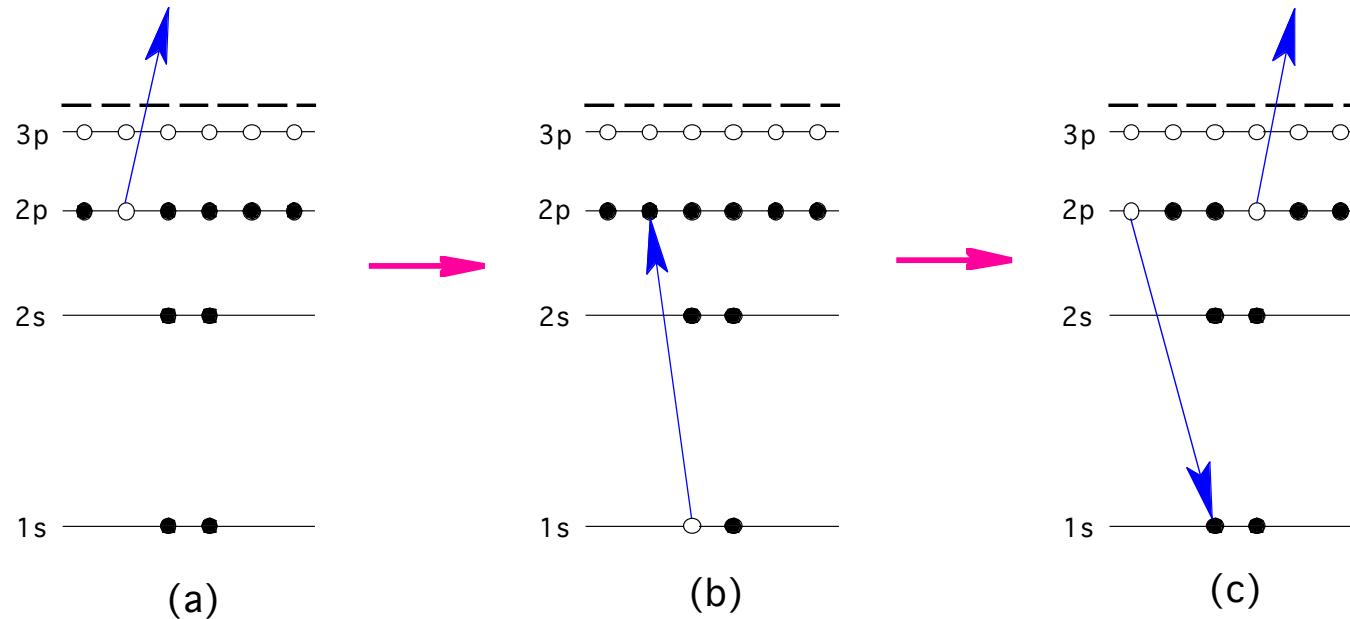
But LCLS linewidth ~ 8 eV!



- Strong $1s \rightarrow 3p$ resonance
 - $\mu_{Ne\ 1s-3p} = 0.01\ ea_0$
 - $\tau_{Ne\ 1s^{-1}} = 2.4\ fs = 100\ a.u.$
- Rabi flopping possible
 - $E_{Ne} \sim 6.3\ a.u.$
 - $I_{Ne} \sim 1.4 \times 10^{18}\ W/cm^2$



Rabi-flopping on 1s - 2p resonance more feasible



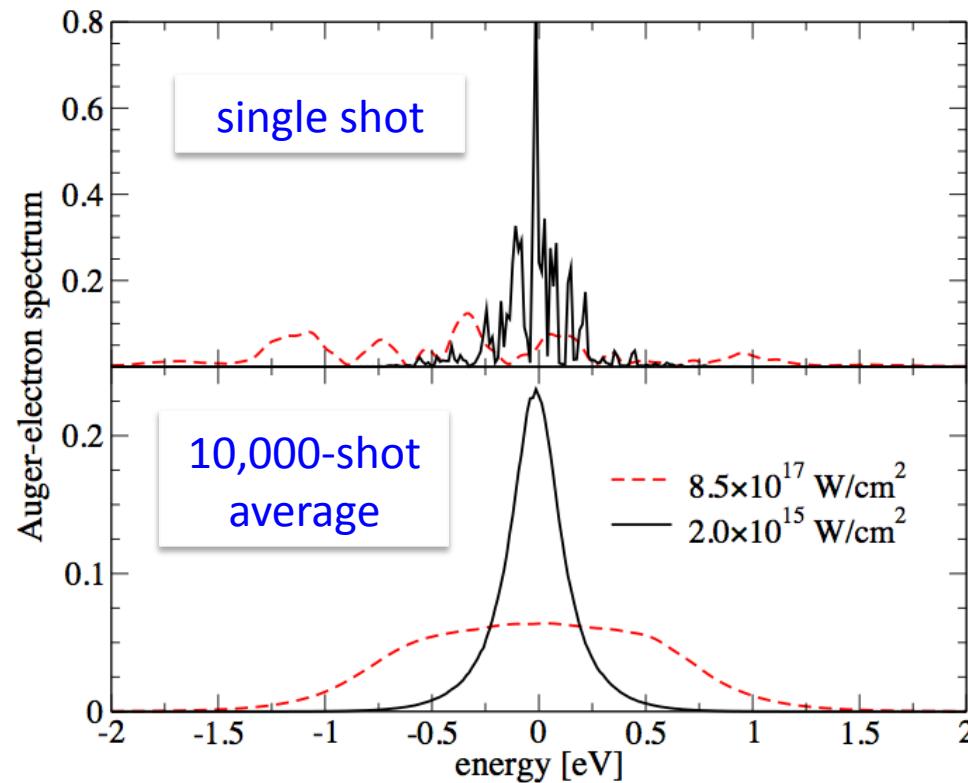
$$E_{x-ray} = 848.6 \text{ eV}$$
$$\sigma_{1s-2p} = 500\sigma_{2p-\infty} = 30 \sigma_{1s-3p}$$

Observe Auger yield when x-rays scanned over 1s - 2p resonance.
Observe broadening at resonance to indicate Rabi flopping

Theory: Rohringer & Santra PRA (2008).



Calculated “Resonant Auger effect at high x-ray intensity”



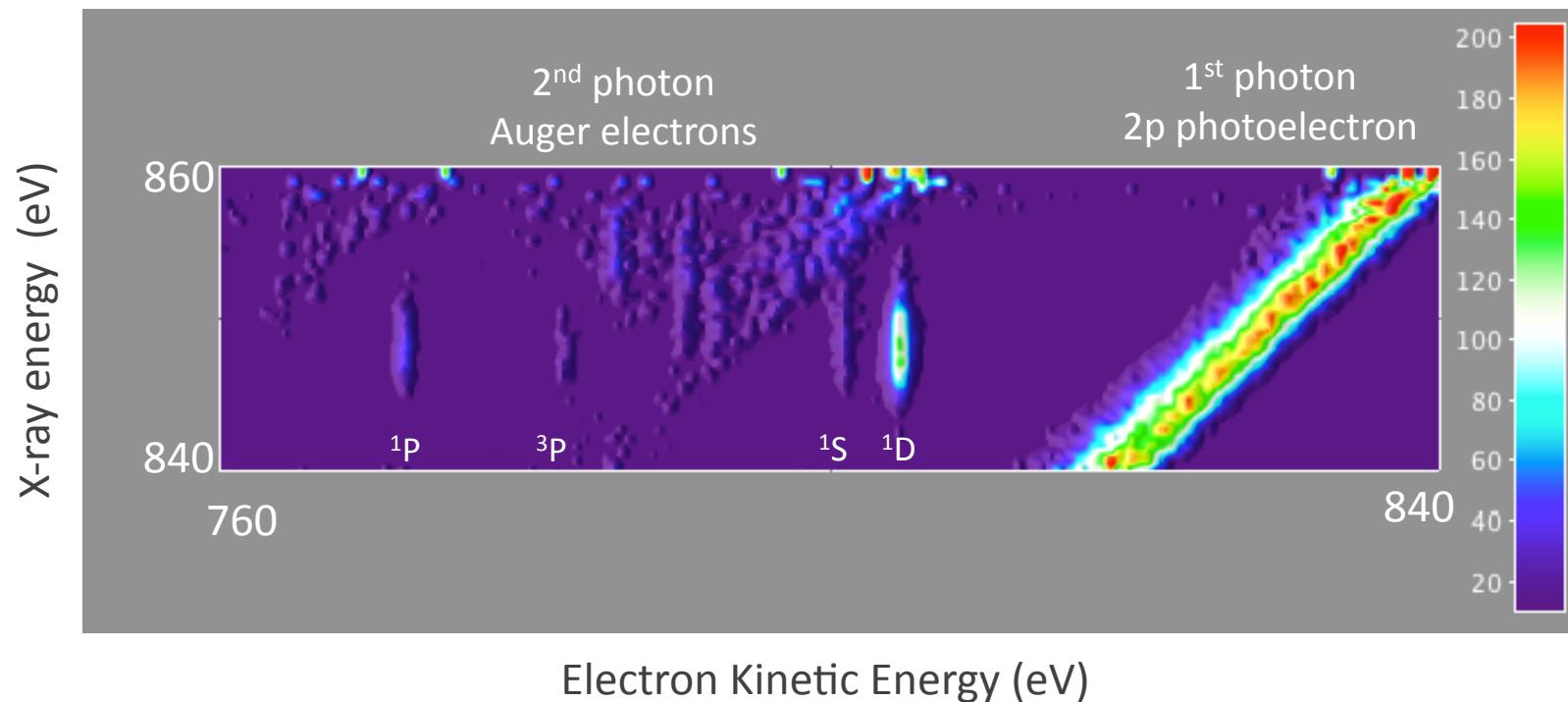
-> Look for Auger line broadening on resonance

N. Rohringer & R. Santra, PRA 77, 053404 (2008)



Electron spectra vs photon energy

using eTOF1 perpendicular to photon polarization to
suppress 2s photoelectrons (40 pC/bunch)

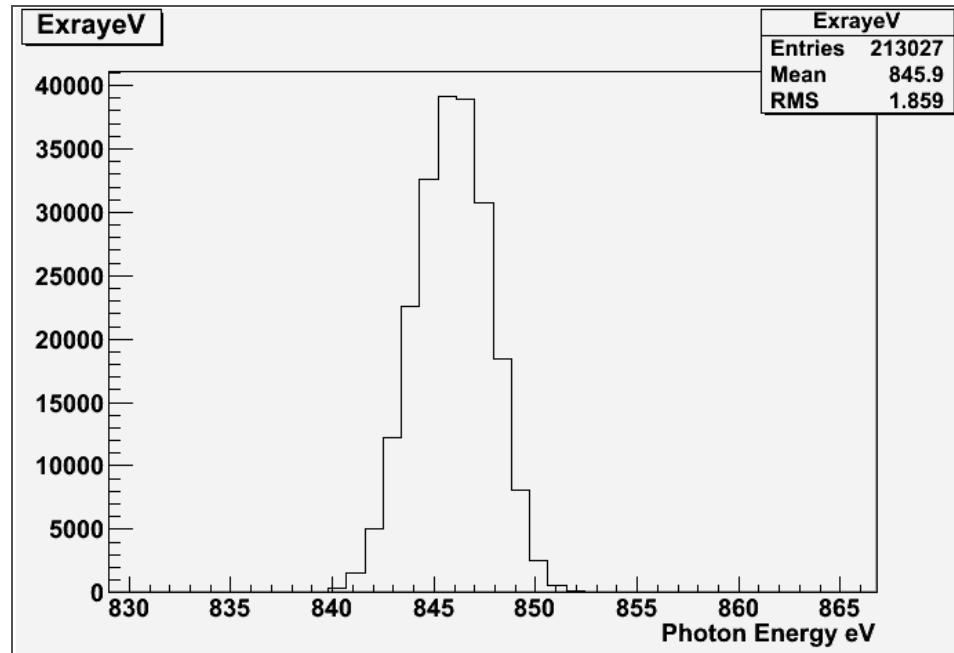


Preliminary from Bertold Krässig



Shot-to-shot photon energy jitter

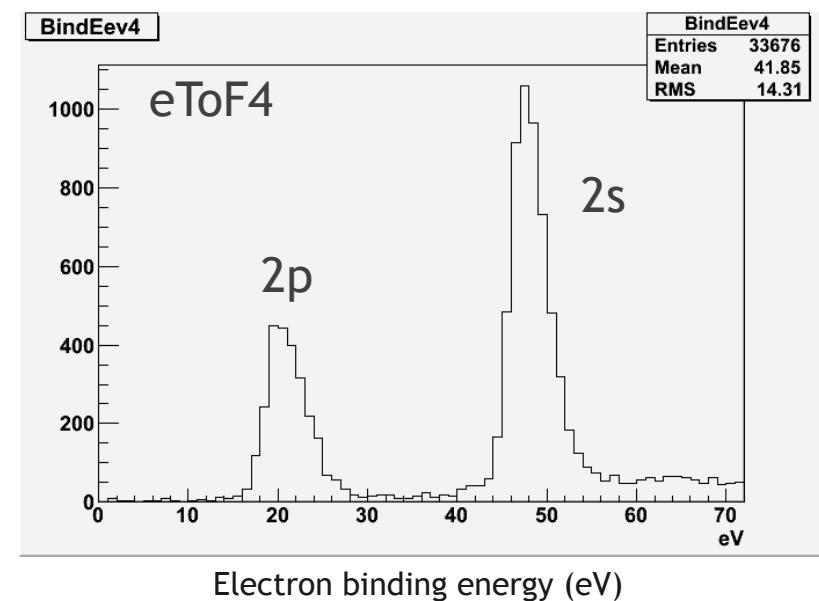
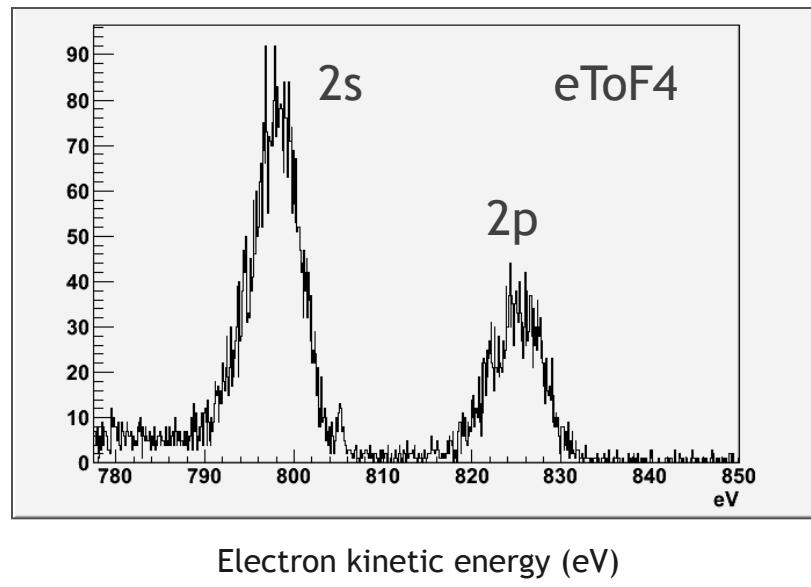
derived from GeV electron bunch energy measurement



Conditions	FWHM photon energy jitter (eV)
40 pC (<10 fs) 850 eV 0.3 mJ 4500 A	4.25
250 pC (100 fs) 787 eV 1.5 mJ 2500 A	4.79
250 pC (100 fs) 769 eV 1.5 mJ 2500 A	5.24



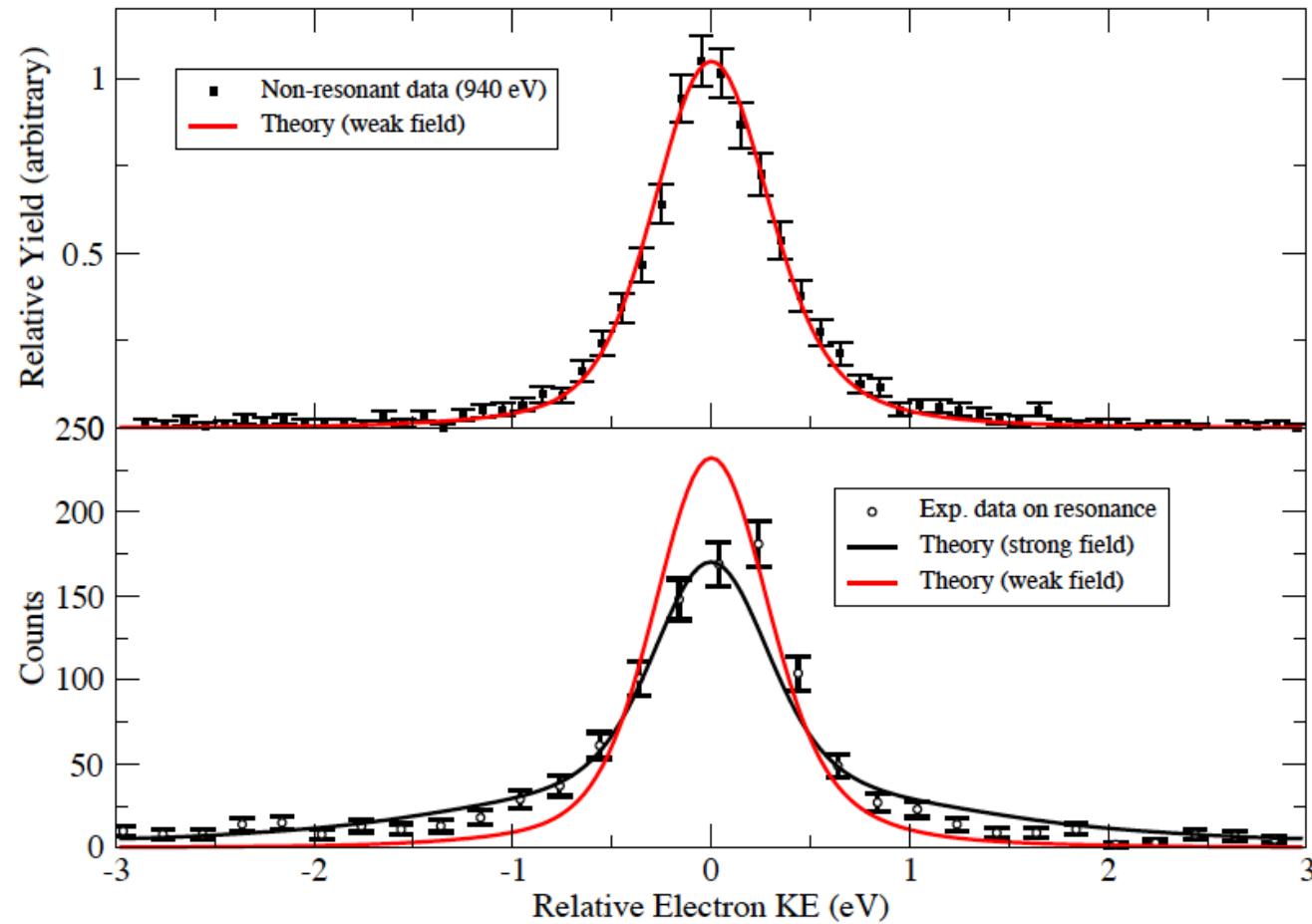
Determination of intrinsic x-ray bandwidth from electron spectra



Conditions	Intrinsic x-ray pulse bandwidth (from 2s photopeak) (eV) (FWHM)	Intrinsic x-ray pulse bandwidth (from 2p photopeak) (eV) (FWHM)	Average bandwidth (eV) (FWHM)	%
40 pC (<10 fs) 850 eV 0.3 mJ 4500 A	4.3	4.5	4.4	0.5 %
250 pC (100 fs) 787 eV 1.5 mJ 2500 A	7.1	7.8	7.45	0.9%
250 pC (100 fs) 769 eV 1.5 mJ 2500 A	7.7	7.8	7.77	1%



Is the ^1D Auger line broadened on $1\text{s}-2\text{p}$ resonance?



X-ray parameters
0.3 mJ, 8.5 fs, $2 \mu\text{m}^2$
(20% transmission)

Theory from N. Rohringer and R. Santra
Preliminary Analysis – E. Kanter



Summary

- Insight into ultraintense x-ray interactions
 - six-photon, ten-electron stripping of neon ($\sim 10^{12}/\mu\text{m}^2$)
 - multiple photon absorption probability high when fluence $> 1/\sigma$
- Intensity-induced x-ray transparency – a general phenomena
 - transient x-ray transparency caused by formation of hollow atoms
 - hollow atoms $\sigma_{\text{scatt}}/\sigma_{\text{abs}}$ is increased
- Femtosecond time-scale atomic processes provide FEL diagnostics
- Straightforward rate equation calculations capture essential physics
- Intense x-rays can “control” inner-shell electron dynamics

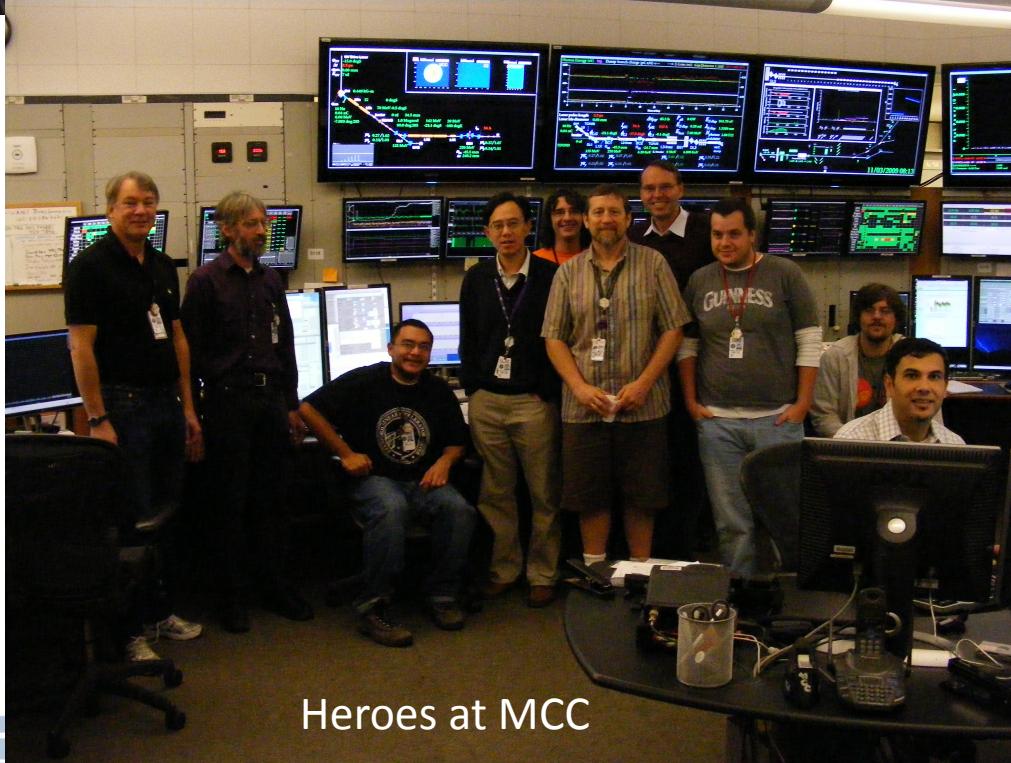




Argonne AMO group Oct 2009



Heroes at AMO Control



Heroes at MCC



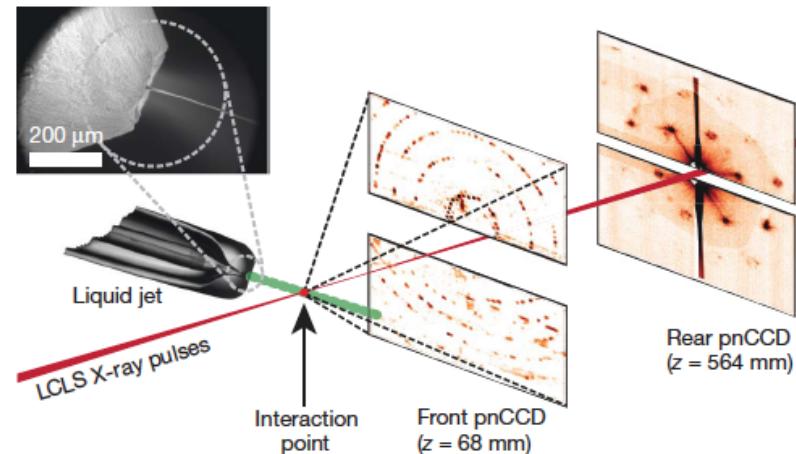


Toward Single Molecule Imaging with X-rays



Femtosecond X-ray protein nanocrystallography

Henry N. Chapman^{1,2}, Petra Fromme³, Anton Barty¹, Thomas A. White¹, Richard A. Kirian⁴, Andrew Aquila¹, Mark S. Hunter³, Joachim Schulz¹, Daniel P. DePonte¹, Uwe Weierstall⁴, R. Bruce Doak⁴, Filipe R. N. C. Maia⁵, Andrew V. Martin¹, Ilme Schlichting^{6,7}, Lukas Lomb⁷, Nicola Coppola^{1†}, Robert L. Shoeman⁷, Sascha W. Epp^{6,8}, Robert Hartmann⁹, Daniel Rolles^{6,7}, Artem Rudenko^{6,8}, Lutz Foucar^{6,7}, Nils Kimmel¹⁰, Georg Weidenspointner^{11,10}, Peter Holl⁹, Mengning Liang¹, Miriam Barthelmess¹², Carl Caleman¹, Sébastien Boutet¹³, Michael J. Bogan¹⁴, Jacek Krzywinski¹³, Christoph Bostedt¹³, Saša Bajt¹², Lars Gumprecht¹, Benedikt Rudek^{6,8}, Benjamin Erk^{6,8}, Carlo Schmidt^{6,8}, André Hämke^{6,8}, Christian Reich⁹, Daniel Pietschner¹⁰, Lothar Strüder^{6,10}, Günter Hauser¹⁰, Hubert Gorke¹⁵, Joachim Ullrich^{6,8}, Sven Herrmann¹⁰, Gerhard Schaller¹⁰, Florian Schopper¹⁰, Heike Soltau⁹, Kai-Uwe Kühnel⁸, Marc Messerschmidt¹³, John D. Bozek¹³, Stefan P. Hau-Riege¹⁶, Matthias Frank¹⁶, Christina Y. Hampton¹⁴, Raymond G. Sierra¹⁴, Dmitri Starodub¹⁴, Garth J. Williams¹³, Janos Hajdu⁵, Nicusor Timneanu⁵, M. Marvin Seibert^{5†}, Jakob Andreasson⁵, Andrea Rocker⁵, Olof Jönsson⁵, Martin Svenda⁵, Stephan Stern¹, Karol Nass², Robert Andritschke¹⁰, Claus-Dieter Schröter⁸, Faton Krasniqi^{6,7}, Mario Bott⁷, Kevin E. Schmidt⁴, Xiaoyu Wang⁴, Ingo Grotjohann³, James M. Holton¹⁷, Thomas R. M. Barends⁷, Richard Neutze¹⁸, Stefano Marchesini¹⁷, Raimund Fromme³, Sebastian Schorb¹⁹, Daniela Rupp¹⁹, Marcus Adolph¹⁹, Tais Gorkhover¹⁹, Inger Andersson²⁰, Helmut Hirsemann¹², Guillaume Potdevin¹², Heinz Graafsma¹², Björn Nilsson¹² & John C. H. Spence⁴



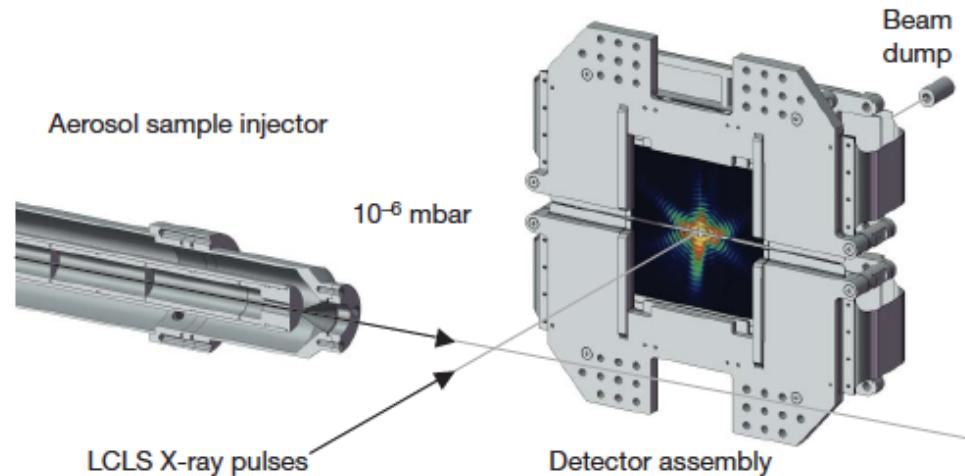
Photosystem I

membrane protein, 1 MDa
3,000,000 diffraction patterns
Crystals 200 nm - 2μm
Resolution 8.5Å
Match synchrotron structure
Dose: 700MGy
Typical synch dose: 30 MGy



Single mimivirus particles intercepted and imaged with an X-ray laser

M. Marvin Seibert^{1*}, Tomas Ekeberg^{1*}, Filipe R. N. C. Maia^{1*}, Martin Svenda¹, Jakob Andreasson¹, Olof Jönsson¹, Duško Odić¹, Bianca Iwan¹, Andrea Rocker¹, Daniel Westphal¹, Max Hantke¹, Daniel P. DePonte², Anton Barty², Joachim Schulz², Lars Gumprecht², Nicola Coppola², Andrew Aquila², Mengning Liang², Thomas A. White², Andrew Martin², Carl Caleman^{1,2}, Stephan Stern^{2,3}, Chantal Abergel⁴, Virginie Seltzer⁴, Jean-Michel Claverie⁴, Christoph Bostedt⁵, John D. Bozek⁵, Sébastien Boutet⁵, A. Alan Miahnahri⁵, Marc Messerschmidt⁵, Jacek Krzywinski⁵, Garth Williams⁵, Keith O. Hodgson⁶, Michael J. Bogan⁶, Christina Y. Hampton⁶, Raymond G. Sierra⁶, Dmitri Starodub⁶, Inger Andersson⁷, Saša Bajt⁸, Miriam Barthelmess⁸, John C. H. Spence⁹, Petra Fromme¹⁰, Uwe Weierstall⁹, Richard Kirian⁹, Mark Hunter¹⁰, R. Bruce Doak⁹, Stefano Marchesini¹¹, Stefan P. Hau-Riege¹², Matthias Frank¹², Robert L. Shoeman¹³, Lukas Lomb¹³, Sascha W. Epp^{14,15}, Robert Hartmann¹⁶, Daniel Rolles^{13,14}, Artem Rudenko^{14,15}, Carlo Schmidt^{14,15}, Lutz Foucar^{13,14}, Nils Kimmel^{17,18}, Peter Holl¹⁶, Benedikt Rudek^{14,15}, Benjamin Erk^{14,15}, André Hömke^{14,15}, Christian Reich¹⁶, Daniel Pietschner^{17,18}, Georg Weidenspointner^{17,18}, Lothar Strüder^{14,17,18,19}, Günter Hauser^{17,18}, Hubert Gorke²⁰, Joachim Ullrich^{14,15}, Ilme Schlichting^{13,14}, Sven Herrmann^{17,18}, Gerhard Schaller^{17,18}, Florian Schopper^{17,18}, Heike Soltau¹⁶, Kai-Uwe Kühnel¹⁵, Robert Andritschke^{17,18}, Claus-Dieter Schröter¹⁵, Faton Krasniqi^{13,14}, Mario Bott¹³, Sebastian Schorb²¹, Daniela Rupp²¹, Marcus Adolph²¹, Tais Gorkhoven²¹, Helmut Hirsemann⁸, Guillaume Potdevin⁸, Heinz Graafsma⁸, Björn Nilsson⁸, Henry N. Chapman^{2,3} & Janos Hajdu¹



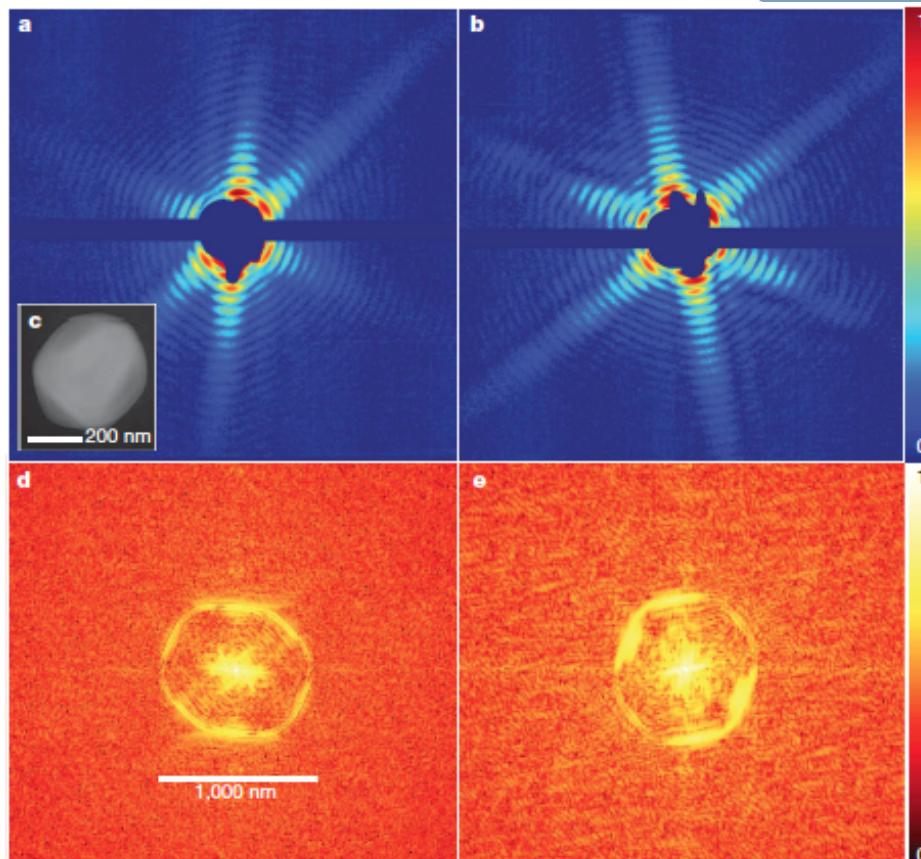
Mimivirus

- Largest known virus – 0.75 µm
- Does not crystallize
- Too large for 3D cryoelectron microscopy
- Single Shot Scattering Pattern
- 32 nm resolution

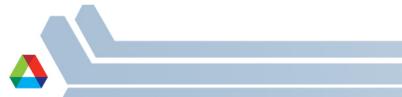
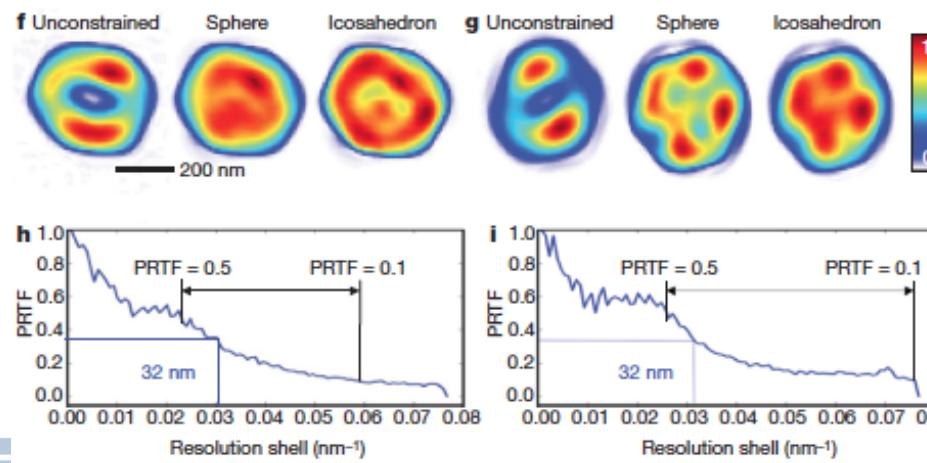


Mimivirus

Diffraction

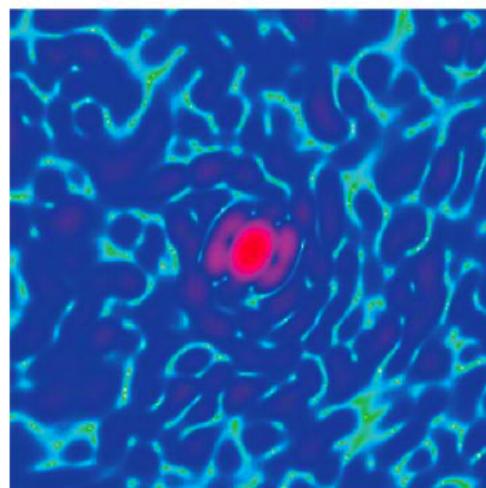
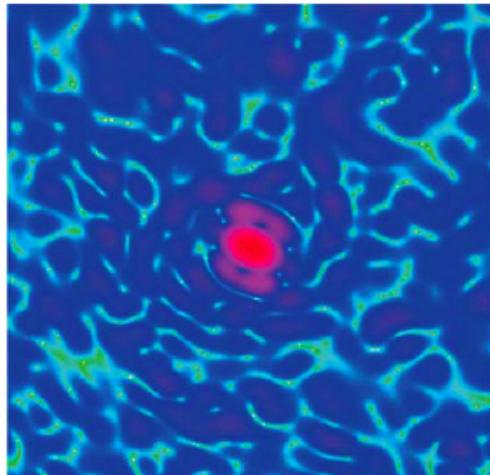


Reconstruction

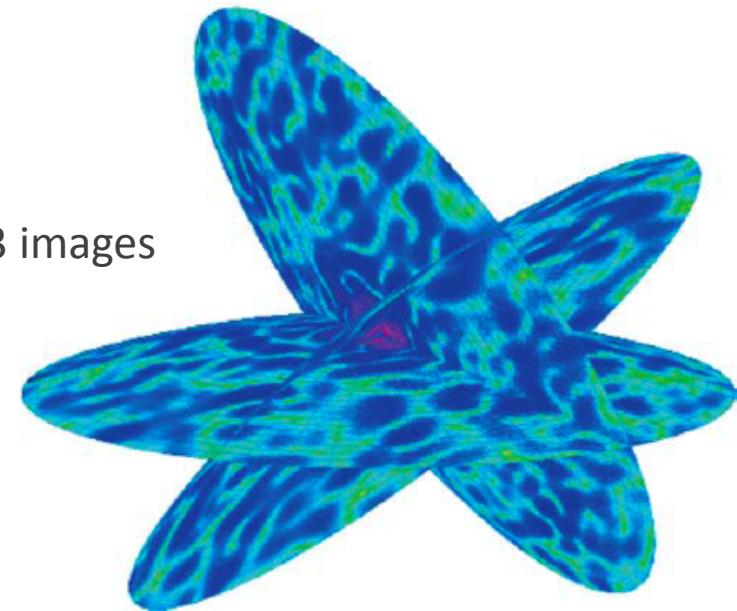


3D image reconstruction: classification + averaging + phase retrieval

2 noisy images - same view?



3 images



Arc gives a 3D fix

Huldt, Sköke, Hajdu, J. Struct. Bio 144, 219 (2003)

Miao, Charalambous, Kirz, Sayre, Nature 400, 342 (1999)



Compare single molecule x-ray imaging to femtosecond nanocrystallography

Photosystem I: nanocrystals

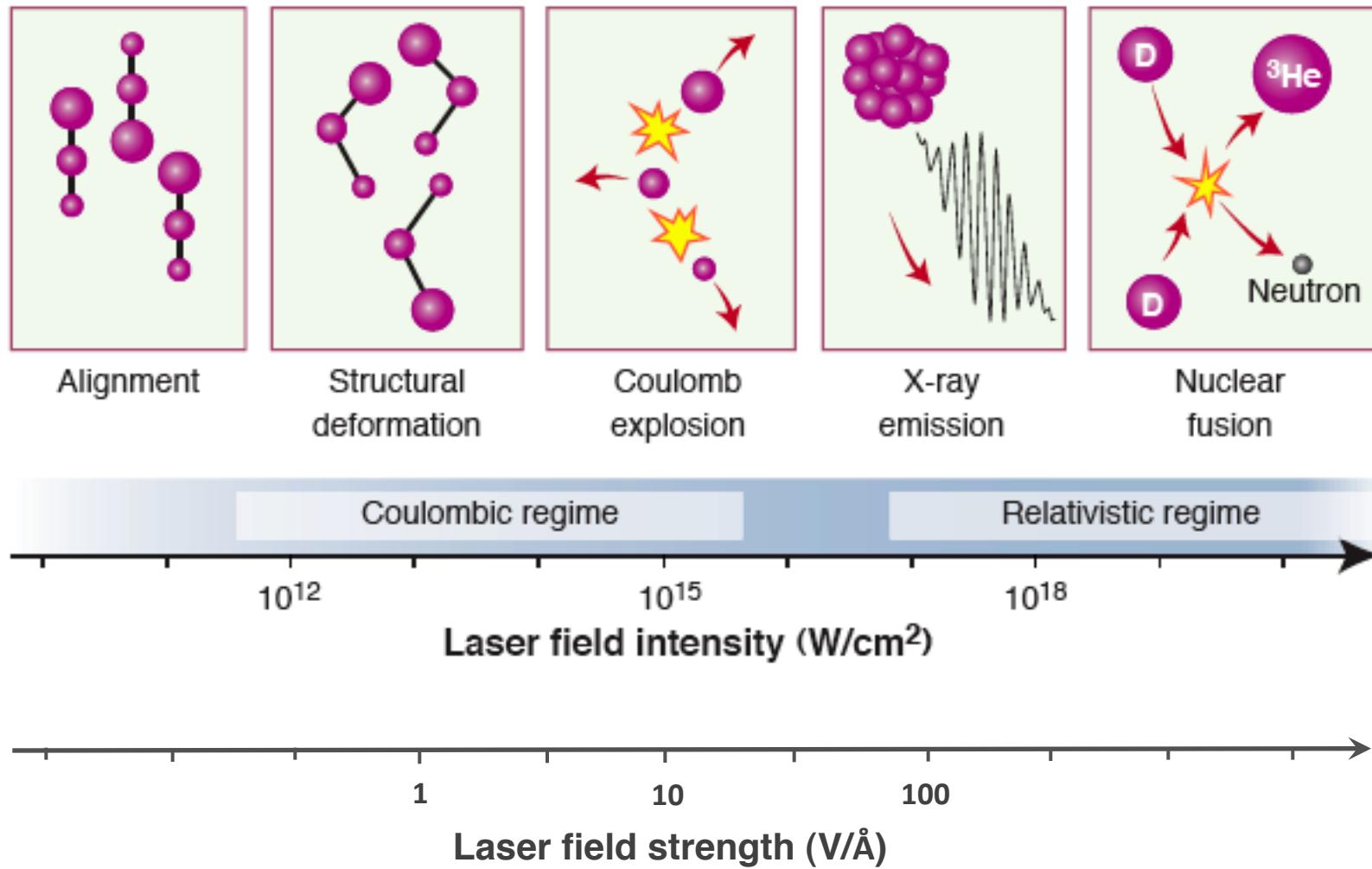
- 10x10x10 unit cell
 $V \sim (500 \text{ nm})^3$
- 10^6 enhancement (n^2)
- Diffraction from focused LCLS pulse
~2 mJ/pulse @ 2000 eV
~9 Å resolution

Ensemble of single molecules

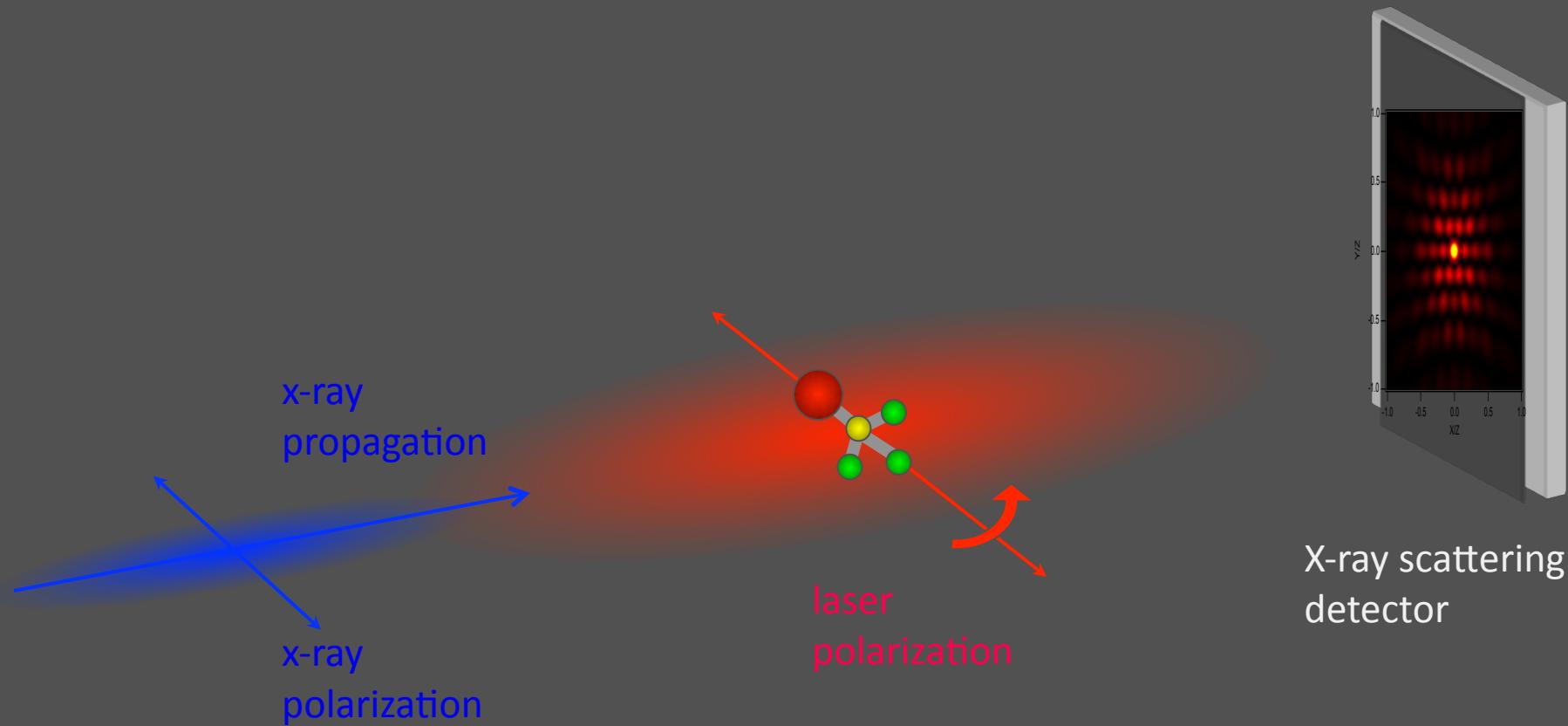
- 10^6 molecules
($100 \mu\text{m}^2 \times 1\text{mm}$) $10^{13}/\text{cm}^3$
- 10^6 enhancement (n)
- Scattering from focused LCLS pulse?
Kupper, Chapman...



Behavior of molecules in strong laser fields



X-ray microprobe of laser-aligned molecules

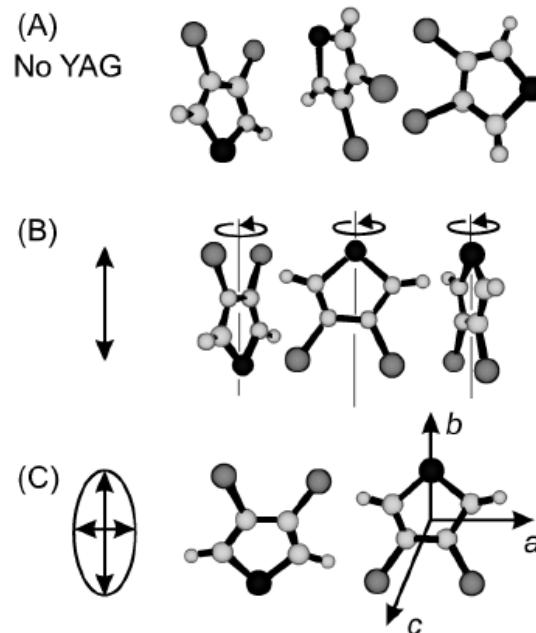


L. Young et al. PRL (2006).

E. R. Peterson et al. APL (2008)

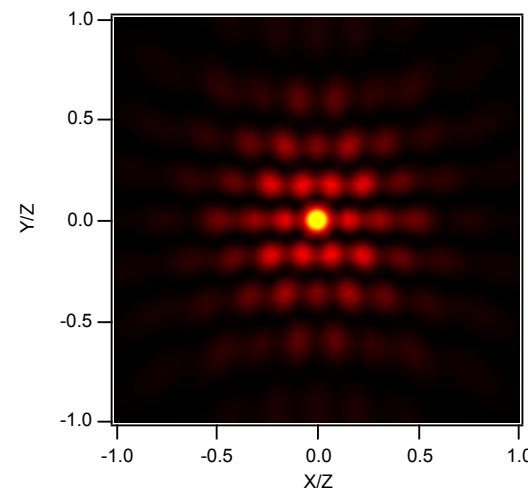
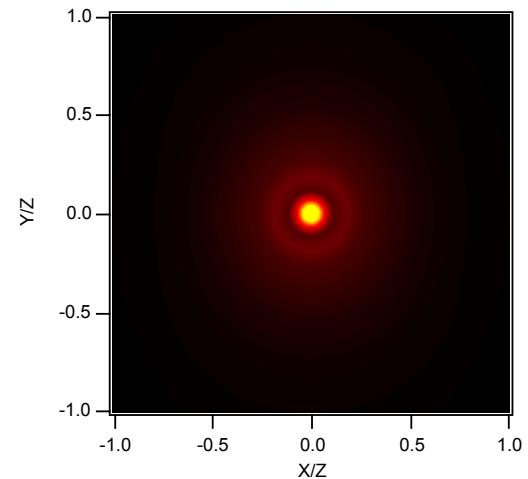
3D - alignment

3-D alignment w/elliptically pol'd fields
3,4 dibromothiophene



J.J. Larsen et al., PRL 85, 2470 (2000)

X-ray scattering, 20 keV



Comparing APS and LCLS x-ray pulses

Flux comparison to the Linac Coherent Light Source (LCLS)

Source	Energy	Max Rep Rate	Photons/pulse	Integrated flux
BioCARS APS	7-17 keV	1000 Hz	3.2×10^{10}	3.2×10^{13}
LCLS	8.2 keV	120 Hz	$\sim 1 \times 10^{12}$	1.2×10^{14}
LCLS (Third harmonic)	24.6 keV	120 Hz	$\sim 1 \times 10^{10}$	1.2×10^{12}



- Time integrated Flux 25% of LCLS
- LCLS time-resolution < 80 fsec
- BioCARS ~100 psec

The University of Chicago



Multi-photon absorption may occur at LCLS: 10^{10} photons/ $1 \text{ fs}/\mu\text{m}^2$

but not at APS: 3×10^{10} photons/ $100 \text{ ps} = 3 \times 10^5$ photons/ $1 \text{ fs}/\mu\text{m}^2$

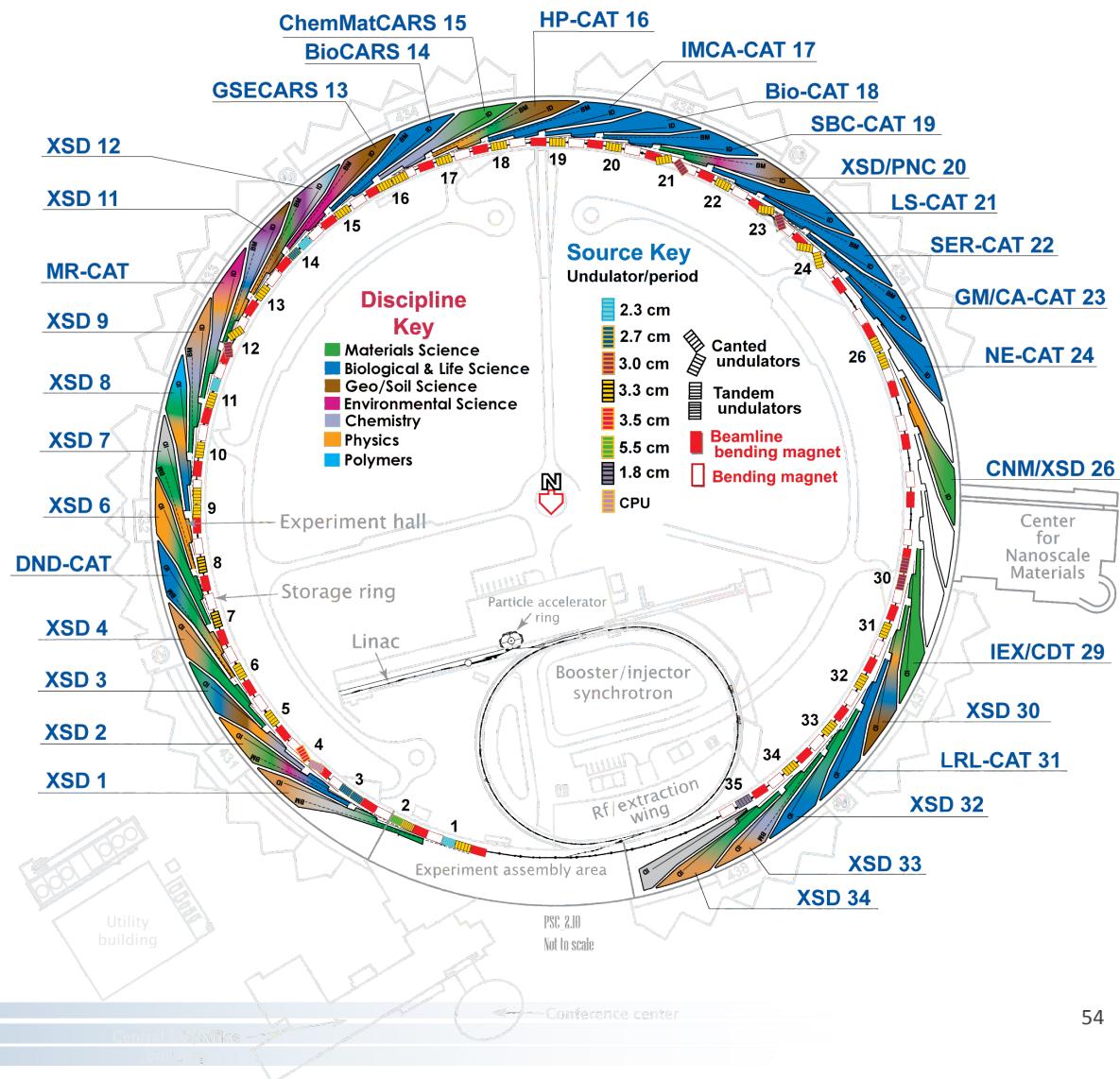
courtesy Tim Graber



The Advanced Photon Source: 7 GeV, dedicated 1996

2010: 62 operating beamlines

- Users in every state & worldwide
- 3537 unique users in FY09
- 1185 peer-reviewed pubs in FY09
- Almost 1/3 of EFRCs identify APS as a major component of proposed work
- New and upgraded beamlines in the last three years include 14-ID, 12-ID, 1-ID, 32-ID, IEX, IXS and Nanoprobe online....
- Today one half of beamlines are operated by XSD



Expanding International Capabilities for X-rays



ESRF, France: upgrading



PETRA-III, Germany: new

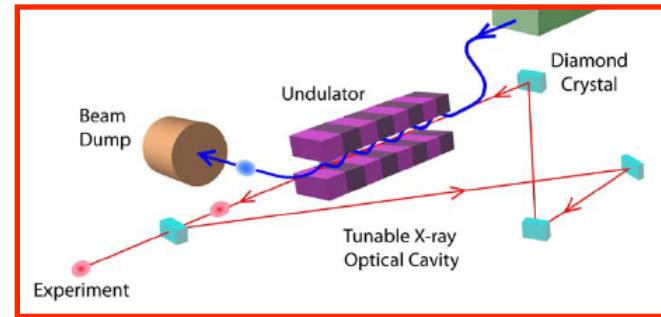


SPring-8, Japan: upgrading

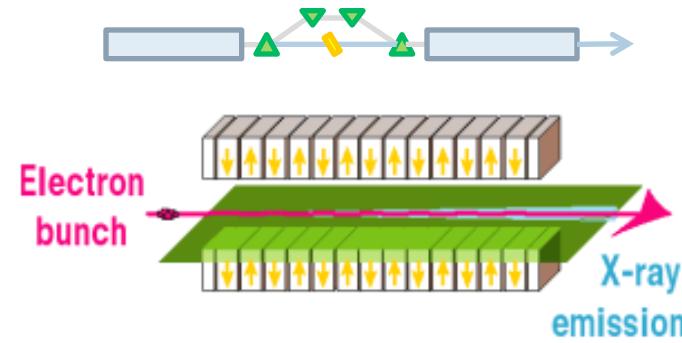


Exciting times for x-ray & laser science just starting!

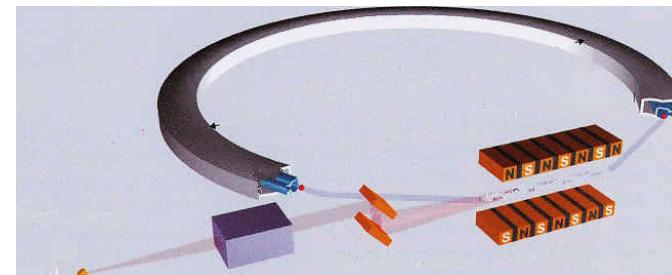
X-ray FEL Oscillator: Full coherence & very high average brightness



Hard X-ray self seeding



3rd Generation SR source:



Adapted from K.J. Kim
56

